A Review of Energy Storage Technologies

For the integration of fluctuating renewable energy

Connolly, David

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For the integration of fluctuating renewable energy

David Connolly
University of Limerick

david.connolly@ul.ie
www.cpi.ul.ie

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Abstract

A brief examination into the energy storage techniques currently available for the integration of fluctuating renewable energy was carried out. These included Pumped Hydroelectric Energy Storage (PHES), Underground Pumped Hydroelectric Energy Storage (UPHES), Compressed Air Energy Storage (CAES), Battery Energy Storage (BES), Flow Battery Energy Storage (FBES), Flywheel Energy Storage (FES), Supercapacitor Energy Storage (SCES), Superconducting Magnetic Energy Storage (SMES), Hydrogen Energy Storage System (HESS), Thermal Energy Storage (TES), and Electric Vehicles (EVs). The objective was to identify the following for each:

1. How it works
2. Advantages
3. Applications
4. Cost
5. Disadvantages
6. Future

A brief comparison was then completed to indicate the broad range of operating characteristics available for energy storage technologies. It was concluded that PHES is the most likely stand-alone technology that will be utilised in Ireland for the integration of fluctuating renewable energy. However, the HESS, TESS, and EVs are the also very promising, but require more research to remove uncertainty surrounding their benefits and costs.

For some countries, CAES could be a more suitable technology than PHES depending on the availability of suitable sites. FBES could also be utilised in the future for the integration of wind, but it may not have the scale required to exist along with electric vehicles. The remaining technologies will most likely be used for their current applications in the future, but further developments are unlikely.

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Nomenclature

Symbol	Description	Unit
A	Area of parallel plates on capacitor	m^2
C	Capacitance	F
E_{CAP}	Energy stored in capacitor	J
E_{COIL}	Energy stored in coil (of SMES device)	J
$E_{KINETIC}$	Total kinetic energy in flywheel	J
F	Force	N (kgm/s^2)
I	Current	A
L	Inductance of coil (in SMES device)	H
P_C	Power Capacity	W (J/s)
S_C	Storage Capacity	Wh
T	Temperature in Kelvin / degrees Celsius	K / °C
V	Voltage	V
d	Distance between parallel plated on capacitor	m
t	Time	h, s
m_f	Mass of flywheel	kg
g	Acceleration due to gravity	m/s^2
$v_{CIRCULAR}$	Circular velocity of flywheel	m/s
ε_0	Permittivity of free space	F/m
ε_r	Relative permittivity/dielectric constant	F/m
η	Efficiency of PHES when pumping or generating	-
η_G	Efficiency of PHES when generating	-
ρ	Density	kg/m^3
σ	Specific strength of flywheel material	Nm/kg

Acronyms and Abbreviations

Symbol	Description
AC	Alternating Current
ACTES	Air-Conditioning Thermal Energy Storage
ATS	Aquifer Thermal Storage
BES	Battery Energy Storage
BOP	Balance-of-Plant
CAES	Compressed Air Energy Storage
DC	Direct Current
DoD	Depth-of-Discharge
DOE	Department of Energy (US)
DTS	Duct Thermal Storage
DSM	Demand Side Management
DSO	Distribution System Operator
EU	European Union
FBES	Flow Battery Energy Storage
FC	Fuel Cell
FES	Flywheel Energy Storage
GW	Gigawatt
GWh	Gigawatt-hour
HESS	Hydrogen Energy Storage System
ICE	Internal Combustion Engine
kW	kilowatt
kWh	kilowatt-hour
LA	Lead-Acid
MJ	Mega joule (1 MJ = 0.28 kWh)
MW	Megawatt
MWh	Megawatt-hour
NaS	Sodium-Sulphur

Symbol	**Description**
NiCd	Nickel-Cadmium
PCS	Power Conversion System
PHES	Pumped Hydroelectric Energy Storage
PSB	Polysulphide-Bromide
SCES	Supercapacitor Energy Storage
SMES	Superconducting Magnetic Energy Storage
T&D	Transmission and Distribution
TES	Thermal Energy Storage
TESS	Thermal Energy Storage System
TSO	Transmission System Operator
UK	United Kingdom
UPS	Uninterruptable Power Supply
US	United States (of America)
VR	Vanadium-Redox
VRLA	Valve Regulated Lead-Acid
ZnBr	Zinc-Bromine

1 Introduction

Energy storage is a well established concept yet still relatively unexplored. Storage systems such as pumped hydroelectric energy storage (PHES) have been in use since 1929 [1], primarily to level the daily load on the electricity network between night and day. However, as the electricity sector is currently undergoing a lot of change, energy storage is starting to become a realistic option for [2]:

1. Restructuring the electricity market.
2. Integrating renewable resources.
3. Improving power quality.
4. Aiding the increase in distributed energy production.
5. Helping the network operate under more stringent environmental requirements.

Energy storage can optimise the existing generation and transmission infrastructures whilst also preventing expensive upgrades. Power fluctuations from renewable resources can their penetration onto electricity networks. However energy storage devices can manage these irregularities and thus aid the implementation of renewable technologies. In relation to conventional power production, energy storage devices can improve overall power quality and reliability, which is becoming more important for modern commercial applications. Finally, energy storage devices can reduce emissions by aiding the transition to newer, cleaner technologies such as renewable resources and the hydrogen economy. Therefore, Kyoto obligations can be met and penalties avoided.

Historically, a number of obstacles have hampered the commercialisation of energy storage devices. Firstly, there are inconclusive benefits from energy storage. Consumers do not understand what exactly the benefits of energy storage are in terms of savings, additional renewables, and power quality. This issue is enhanced by the high capital costs typically associated with energy storage technologies and the lack of experience for many participants involved including investors, transmissions system operators (TSOs), and market designers. Consequently, it is even uncertain who should pay for energy storage? Some participants view storage as 'grid infrastructure', especially in markets where energy storage is primarily dispatched as a grid asset. However, other participants view it as another generator which should be built and operated by individual investors. If this is the case, then electricity markets need to be structured to accommodate energy storage: for example regulating markets need to be liberalised and energy storage should be able to bid for both demand and generation on the electricity market.

Even with these concerns, it is still envisaged that as renewable resources and power quality become increasingly important, energy storage costs are expected to decline and concerns in relation to their deployment should be resolved. Therefore, this report was carried out to identify the numerous different types of energy storage devices currently available. The parameters used to describe an energy storage device are defined in section 0, followed by a description its components in section 0. Subsequently, some typical energy storage applications are described in section 4 and in section 0, each energy storage technique currently available is analysed under the following key headings: operation; advantages; applications; cost; disadvantages; and future potential. Finally, in section 6 a brief comparison of the various technologies is provided which creates the conclusions outlined in 7.

1.1 Energy Storage for Ireland

In order to reduce greenhouse gases, Ireland's primary objective is to produce at least 40% of its electricity from renewable resources by 2020 [3]. In line with this, Ireland's wind capacity reached approximately 1000 MW in 2008, which Table 1-1 indicates is approximately 13% of the total Irish generating capacity. However, not only did this only provided 8.1% on Ireland's total electricity demand [4], but previous research has indicated that grid stability can be affected once wind capacity passes 800 MW [5]. As a result, Ireland will need to address the effects of wind intermittency in the immediate future as it progresses towards its 2020 targets.

Table 1-1: Conventional and wind generation capacity for Ireland and Northern Ireland in 2008#.

Item	Republic of Ireland (MW)	Northern Ireland (MW)	All-Island (MW)
Total Conventional Capacity (MW)	6245	1968	8213
Total Wind Capacity (MW)	1000♦	182*	1182♦
Total	7245	2150	9395

#Data is correct as of 18th January 2008.
♦Numbers have been rounded for convenience.
***Will increase to 408 MW by August 2009.**

Energy storage on an electric grid provides all the benefits of conventional generation such as enhanced grid stability, optimised transmission infrastructure, high power quality, increased renewable energy penetration, and increased wind farm capacity. However, almost all energy storage technologies produce no carbon emissions during generation and do not rely on imported fossil fuels. As a result, energy storage is a very attractive option for increasing wind penetration onto the electric grid when it is needed.

Currently Ireland's solution to the intermittency of wind generation is primarily based on increased grid interconnection [6]. Hence, the Irish TSO (EirGrid) is in the process of constructing a 500 MW interconnector from Ireland to Wales that will allow for importing and exporting of electricity to and from Britain. Effectively, Britain will be Ireland's 'storage' device: excess electricity can be sold when the wind is blowing and electricity can be imported when it is not. However, unlike an energy storage device, the availability of an interconnector will not only depend on the Irish energy system, but on the British one as well.

Denmark which not only has the largest penetration of wind energy in the world, but is also a very similar country to Ireland in terms of population, energy demand, and renewable resources, also built large interconnectors to neighbouring countries Germany, Norway and Sweden (see Table 1-2). However, the Danish experience has indicated that interconnection is not an ideal solution for the integration of wind power, as they often export their wind power cheaper than the electricity that is imported. When excess wind power is available Denmark needs to get export it, so its neighbouring counties can buy wind power from Denmark at a cheap price. However, when wind production is low, the neighbouring countries can then sell power back to Denmark at a higher rate, as the Danish system must meet demand. Although Denmark often makes a profit under these circumstances, the value of its wind energy is reduced. As a result, Danish studies indicate that the financial benefit associated with their large interconnection is small compared to the implementation of other technologies which would create flexibility within the Danish energy system [7]. Similarly, if Ireland uses Britain as a power sink/source to accommodate wind power, Ireland too could reduce the value of its wind power, by exporting cheap and importing expensive electricity.

To conclude, energy storage technologies may provide a source of flexibility that enables Ireland to utilise its wind power at lower socio-economic costs than solutions such as interconnection. By using energy storage with or instead of interconnection, Ireland could potentially develop an independent, stable, and green electric grid. Based on this possibility alone, it is worth assessing the various types of storage technologies that exist so an assessment of large-scale energy storage in Ireland can be completed.

Table 1-2: Grid interconnection in and out of Denmark.

Country	Interconnection From Denmark (MW)	Interconnection To Denmark (MW)
Germany	1200	800
Norway	950	1000
Sweden	610	580
Total	2760	2380

2 Energy Storage Parameters

Throughout this report, various parameters of the different energy storage technologies that exist will be discussed. These parameters are defined below for clarity:

- Power Capacity: is the maximum instantaneous output that an energy storage device can provide, usually measured in kilowatts (kW) or megawatts (MW).
- Energy Storage Capacity: is the amount of electrical energy the device can store usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh).
- Efficiency: indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge the device.
- Response Time: is the length of time it takes the storage device to start releasing power.
- Round-Trip Efficiency: indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge and discharge the device.

2.1 Battery/Flow Battery Only

For electrochemical based storage technologies such as advanced batteries and flow batteries, there is specific terminology, which is:

- Charge-to-Discharge Ratio: is the ratio of the time it takes to charge the device relative to the time it takes to discharge the device i.e. if a device takes 5 times longer to charge than to discharge, it has a charge-to-discharge ratio of 5:1.
- Depth-of-Discharge (DoD): is the percentage of the battery capacity that is discharged during a cycle.
- Memory Effect: If certain batteries are never fully discharged they ‘remember’ this and lose some of their capacity.

3 Energy Storage Components

Before discussing the technologies, a brief explanation of the components within an energy storage device are discussed. Every energy storage facility is comprised of three primary components:

1. Storage Medium
2. Power Conversion System (PCS)
3. Balance of Plant (BOP)

3.1 Storage Medium

The storage medium is the 'energy reservoir' that retains the potential energy within a storage device. It ranges from mechanical (PHES), chemical (BES) and electrical (SMES) potential energy.

3.2 Power Conversion System (PCS)

It is necessary to convert from alternating current (AC) to direct current (DC) and vice versa, for all storage devices except mechanical storage devices e.g. PHES and CAES [8]. Consequently, a PCS is required that acts as a rectifier while the energy device is charged (AC to DC) and as an inverter when the device is discharged (DC to AC). The PCS also conditions the power during conversion to ensure that no damage is done to the storage device.

The customization of the PCS for individual storage systems has been identified as one of the primary sources of improvement for energy storage facilities, as each storage device operates differently during charging, standing and discharging [8]. The PCS usually costs from 33% to 50% of the entire storage facility. Development of PCSs has been slow due to the limited growth in distributed energy resources e.g. small scale power generation technologies ranging from 3 to 10,000 kW [9].

3.3 Balance-of-Plant (BOP)

These are all the devices that:

- Are used to house the equipment
- Control the environment of the storage facility
- Provide the electrical connection between the PCS and the power grid

It is the most variable cost component within an energy storage device due to the various requirements for each facility. The BOP "typically includes electrical interconnections, surge protection devices, a support rack for the storage medium, the facility shelter and environmental control systems" [8].

"The balance-of-plant includes structural and mechanical equipment such as protective enclosure, heating/ventilation/air conditioning (HVAC), and maintenance/auxiliary devices. Other BOP features include the foundation, structure (if needed), electrical protection and safety equipment, metering equipment, data monitoring equipment, and communications and control equipment. Other cost such as the facility site, permits, project management and training may also be considered here" [2].

4 Energy Storage Applications

Later this report will outline how unique each energy storage technique is. Due to these unique characteristics of the various techniques available, there are a wide range of applications for energy storage devices. These include [2]:

1. End-use applications
2. Emergency back-up
3. Transmission and distribution stabilisation
4. Transmission upgrade deferral
5. Load management
6. Renewable energy integration
7. Demand Side Management (DSM)

4.1 End-Use Applications

The most common end-use application for energy storage is power quality, which primarily consists of voltage and frequency control. Transit and end-use ride-through are applications requiring short power durations and fast response times, in order to level fluctuations, prevent voltage irregularities, and provide frequency regulation. This is primarily used on sensitive processing equipment and thus the capacities required are usually less than 10 MW.

4.2 Emergency Back-Up

This is a type of uninterruptable power supply (UPS) except the units must have longer energy storage capacities. The energy storage device must be able to provide power while generation is cut altogether. Power ratings of 1 MW for durations up to one day are most common.

4.3 Transmission and Distribution Stabilisation

Energy storage devices are required to stabilise the system after a fault occurs on the network by absorbing or delivering power to generators when needed to keep them turning at the same speed. These faults induce phase angle, voltage, and frequency irregularities that are corrected by the storage device. Consequently, fast response (seconds) and high power ratings (1 MW to 10 MW) are essential.

4.4 Transmission Upgrade Deferral

Transmission line upgrades are usually separated by decades and must be built to accommodate likely load and generating expansions. Consequently, energy storage devices are used instead of upgrading the transmission line until such time that it becomes economical to do so. Typically, transmission lines must be built to handle the maximum load required and hence it is only partially loaded for the majority of each day. Therefore, by installing a storage device the power across the transmission line can maintained a constant even during periods of low demand. When the demand increases, the storage device is discharged to prevent the need for extra capacity on the transmission line. Therefore, upgrades in transmission line capacities can be avoided. Storage devices for this application typically have a power capacity ranging from the kW scale to several hundred megawatts along with a storage capacity of 1 to 3 hours. Currently the most common alternative is portable generators; with diesel and fossil fuel power generators as long term solutions and biodiesel generators as a short term solution.

4.5 Load Management

There are two different aspects to load management: load levelling and load following. Load levelling uses off-peak power to charge the energy storage device which can then be discharged during peak demand. Many international electricity markets trade on a spot market utilising half-hourly trading periods, each with a unique cost per unit of electricity generated (€/MWh). This price can vary significantly over a 24-hour period due to the relative change in electricity demand. For example, Figure 4-1 indicates that in 2009, the average electricity price at 18:30 was approximately 300% the average electricity price at 04:00 on the Irish electricity market. Therefore, energy storage devices can be charged during these off-peak hours at night and then used to generate electricity when it is the most expensive, during short peak production periods in the evening. Not only does this enable the energy storage unit to maximise its profits, but it can also reduce the cost of operating the system.

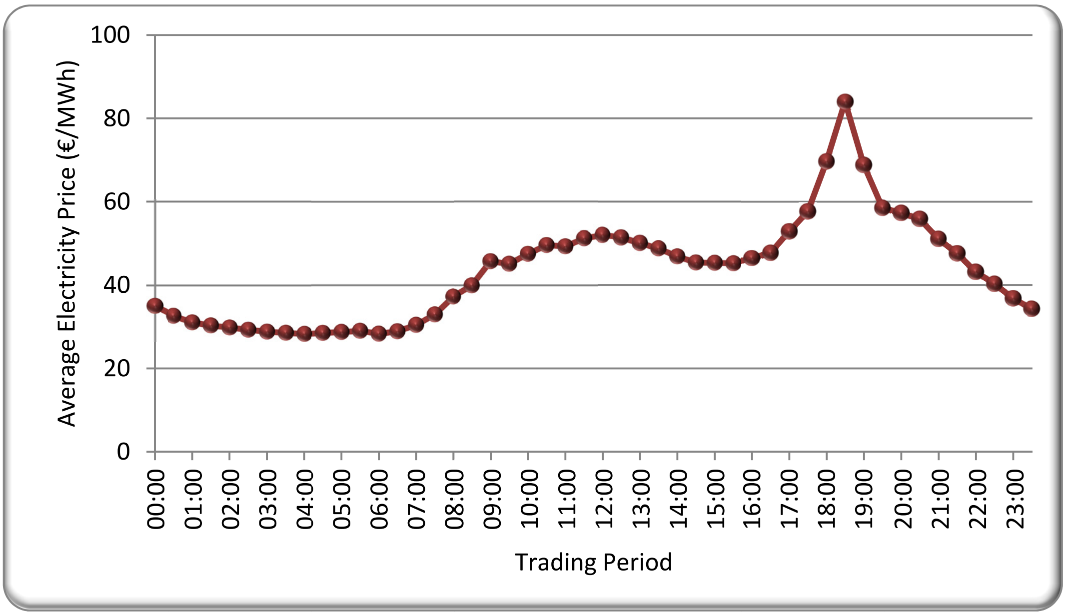


Figure 4-1: Average ex-post electricity price for each trading period on the Irish electricity in 2009 [10].

For load following, the energy storage device acts as a sink when demand falls below production levels and as a source when demand is above production levels. Therefore, the storage can be used to maintain ancillary services and reserve on the electricity grid. Spinning reserve is classified under two categories: fast response and conventional. For fast response spinning reserve, the power capacity must be kept in a state of 'hot standby' so it can respond to network abnormalities in seconds. For conventional spinning reserve, the power capacity requires a slower response of approximately 5-15 minutes.

Energy storage devices used for load management usually require power ratings of 10 MW to 400 MW and fast response times. It utilised for spinning reserve, then the energy storage will usually be required between 20 to 50 times per year.

4.6 Renewable Energy Integration

When analysing the implications of large-scale wind energy on electricity grids, Weisser and Garcia stated that there should be no technical issues for instantaneous wind penetrations up to 20% [11]. In the future, Lundsager et al. estimates that a maximum wind penetration of 25-50% is feasible within the electricity sector [12]. However, Lundsager et al. also stated that the feasibility of very high wind penetrations decreases dramatically when the size of the electricity grid increases from 100 kW to 10 MW: for a 100 kW grid a wind penetration of 80% is feasible, but for a 10 MW grid a wind penetration of only 20% is feasible [12]. The authors concluded that primary reason for this dramatic reduction in feasible wind penetrations was due to the lack of energy storage on the grid [12]. Besides wind, this conclusion can also be made for many other forms of intermittent renewable energy such as solar, tidal, and photovoltaic.

Using its load following capabilities, energy storage can be used to match the output from renewable resources to the demand required. This is displayed in Figure 4-2 using the electricity demand and extrapolated wind data from the Irish energy system based on the 17th April 2008. During the night-time valley wind exceeded demand and thus it was sent to the storage device. When there was a shortfall at approximately 07:00, the storage discharged to ensure demand was met. Alternatively, the storage could be used to maximise the profits from a wind farm by storing renewable energy which is generated during off-peak time periods, but discharging during peak hours, which Figure 4-1 illustrates have much larger electricity prices. Finally, energy storage could also be used to smooth the output fluctuations from an individual wind farm and thus increase the quality of power being delivered from it.

A storage system used with renewable energy could have a power capacity ranging from 10 kW to several hundred megawatts, depending on the capacity of renewable energy and structure of the energy system being considered. Also, it must have a very fast response time (less than a second in some cases), excellent cycling characteristics, and a good lifespan (100 to 1,000 cycles per year).

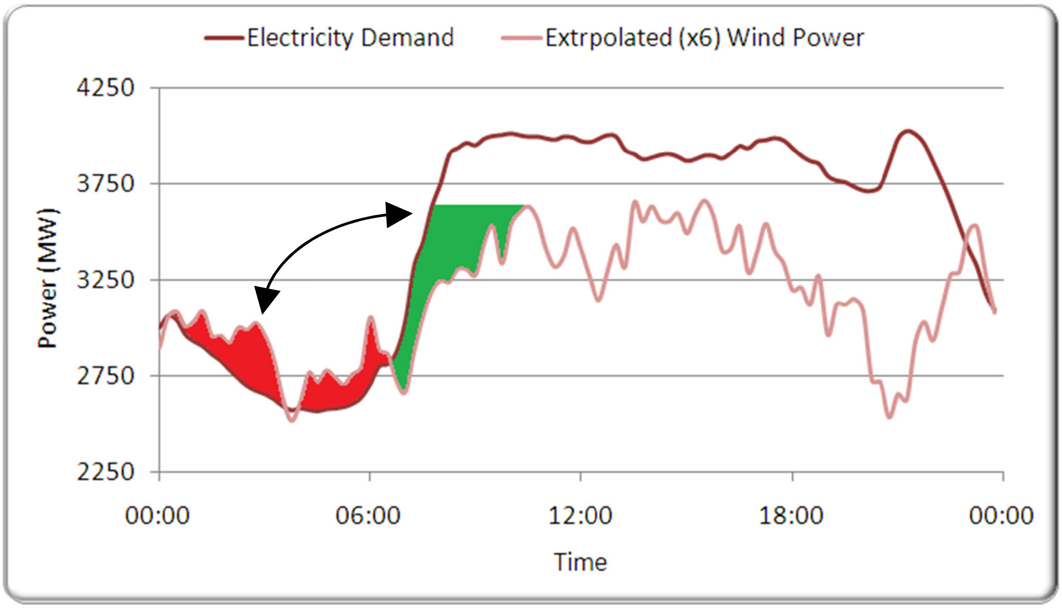
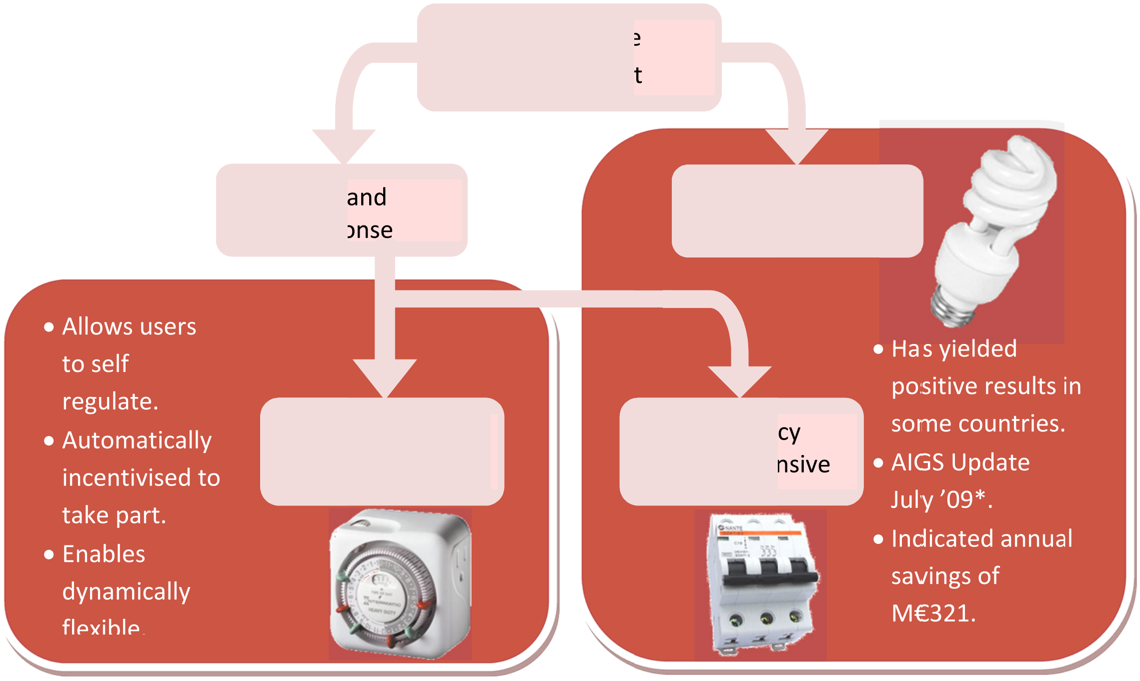


Figure 4-2: Integration of extrapolated (x6) wind power using energy storage on the Irish electricity grid.

4.7 Demand Side Management (DSM)

DSM involves actions that encourage end-users to modify their level and pattern of energy usage. As outlined in Figure 4-3, the level of energy is usually reduced using energy efficiency, which is not generally associated with energy storage. However, the pattern of energy usage is typically altered using price responsive or load responsive demand shifting. Hence, energy storage can aid each of these by creating flexibility as well as providing backup generation. Conversely, DSM can be used to reduce the amount of energy storage capacity required in order to improve the network. Currently, many countries are promoting the use of DSM as a tool for the integration of renewable resource using similar principals to energy storage. Therefore, as smart networks become more advanced, DSM either with or instead of energy storage could become a realistic alternative.



***The AIGS [6] is the basis for Ireland's renewable energy targets. It was updated in 2009 to include DSM [13].**

Figure 4-3: Role of demand side management on electricity grids [14].

5 Energy Storage Techniques

In this section, each of the energy storage techniques identified are analysed under the following key headings: operation and advantages; applications; cost; disadvantages; and future potential. In total 11 types were considered, which included:

1. Pumped hydroelectric energy storage (PHES)
2. Underground pumped hydroelectric energy storage (UPHES)
3. Compressed air energy storage (CAES)
4. Battery energy storage (BES), which included:
   - 4.1 Lead-acid (LA)
   - 4.2 Nickel-cadmium (NiCd)
   - 4.3 Sodium-sulphur (NaS)
5. Flow battery energy storage (FBES), which included:
   - 5.1 Vanadium-redox (VR)
   - 5.2 Polysulphide-bromide (PSB)
   - 5.3 Zinc-bromine (ZnBr)
6. Flywheel energy storage (FES)
7. Supercapacitor energy storage (SCES)
8. Supermagnetic energy storage (SMES)
9. Hydrogen energy storage system (HESS)
10. Thermal energy storage (TES), which included:
    - 10.1 Air-conditioning thermal energy storage (ACTES)
    - 10.2 Thermal energy storage system (TESS)
11. Electric vehicles (EVs)

The various techniques are purposely explained in this order based on their capabilities and hence typical applications. This is discussed in more detail when the various energy storage techniques are compared in section 6. No energy storage technologies were excluded prior to this investigation and hence, every energy storage technology associated with the integration of fluctuating renewable energy in the literature was included for consideration.

5.1 Pumped Hydroelectric Energy Storage (PHES)

Pumped hydroelectric energy storage is the most mature and largest storage technique available. It consists of two large reservoirs located at different elevations and a number of pump/turbine units (see Figure 5-1). During off-peak electrical demand, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed. Once required (i.e. during peak electrical production) the water in the upper reservoir is released through the turbines, which are connected to generators that produce electricity. Therefore, during production a PHES facility operates in a similar way to a conventional hydroelectric system.

The efficiency of modern pumped storage facilities is in the region of 70% - 85%. However, variable speed machines are now being used to improve this [15]. The efficiency is limited by the efficiency of the pump/turbine unit used in the facilities [2].

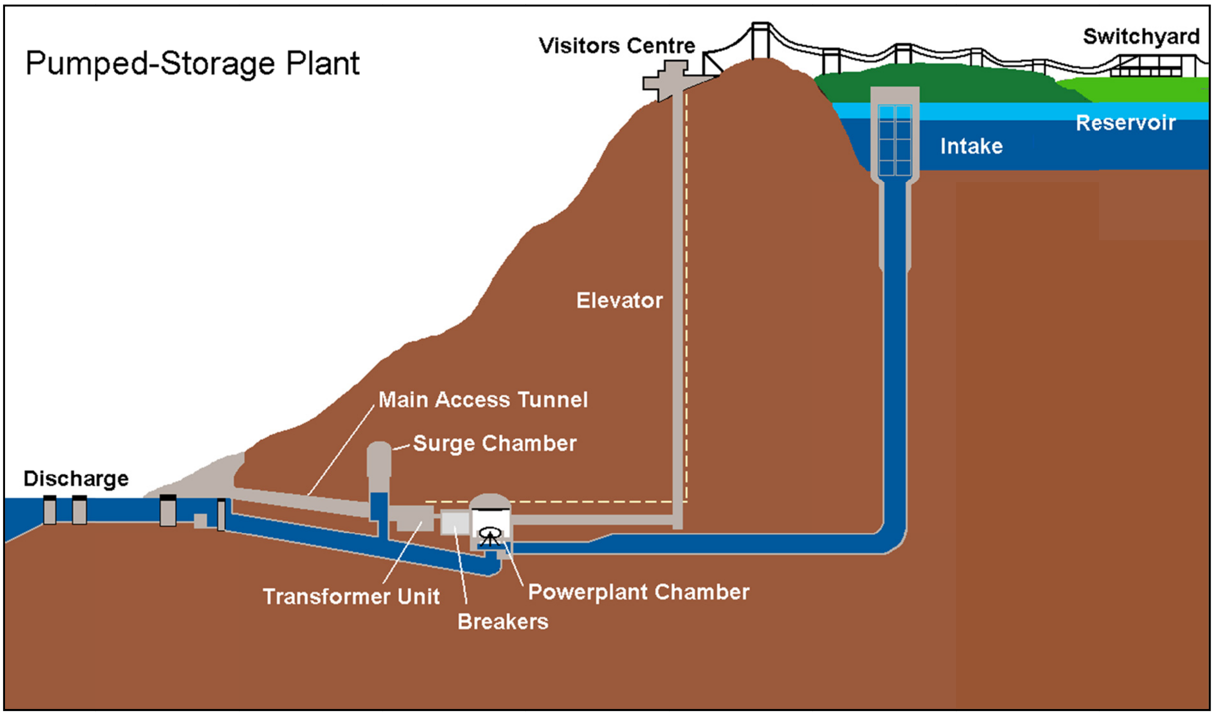


Figure 5-1: Layout of a pumped hydroelectric energy storage facility [16].

Until recently, PHES units have always used fresh water as the storage medium. However, in 1999 a PHES facility using seawater as the storage medium was constructed [17], see Figure 5-2; corrosion was prevented by using paint and cathodic protection. A typical PHES facility has 300 m of hydraulic head (the vertical distance between the upper and lower reservoir). The power capacity (kW) is a function of the flow rate and the hydraulic head, whilst the energy stored (kWh) is a function of the reservoir volume and hydraulic head. To calculate the mass power output of a PHES facility, the following relationship can be used [18]:

$$P_C = \rho g Q H \eta \tag{1}$$

Where:
P_C = power capacity in Watts (W)
ρ = mass density of water in kg/m^3
g = acceleration due to gravity in m/s^2
Q = discharge through the turbines in m^3/s
H = effective head in m
η = efficiency of the PHES when pumping or generating

And to evaluate the storage capacity of the PHES the following must be used [19]:

$$S_C = \frac{\rho g H V \eta_G}{3.6x10^9} \tag{2}$$

Where:
S_C = storage capacity in megawatt-hours (MWh)
V = volume of water that is drained and filled each day in m^3
ρ = mass density of water in kg/m^3
g = acceleration due to gravity in m/s^2
H = effective head in m
η_G = efficiency of the PHES when generating

It is evident that the power and storage capacities are both dependent on the head and the volume of the reservoirs. However, facilities are usually designed with the greatest hydraulic head possible rather than largest upper reservoir possible due to cost. It is much cheaper to construct a facility with a large hydraulic head and small reservoirs, than to construct a facility of equal capacity with a small hydraulic head and large reservoirs because:

1. Less material needs to be removed to create the reservoirs required
2. Smaller piping is necessary, hence, smaller boreholes during drilling
3. The turbine is physically smaller

Currently, there is over 90 GW in more than 240 PHES facilities in the world, which is roughly 3% of the world's global generating capacity. Each individual facility can store from 30 MW to 4,000 MW (15 GWh) of electrical energy [2].

Figure 5-2: Photograph of a pumped hydroelectric storage facility using seawater [17].

5.1.1 Applications

As well as large storage capacities, PHES also has a fast reaction time and hence load-levelling is an ideal application. Figure 5-3 demonstrates how a real-world PHES facility provides load-levelling capabilities to an electric grid, by pumping using cheaper baseload power at night and generating during peak demand in the day. Facilities can have a reaction time as short as 10 minutes or less from complete shutdown (or from full reversal of operation) to full power [8]. In addition, if kept on standby, full power can even be reached within 10 to 30 seconds.

Also, with the recent introduction of variable speed machines, PHES systems can now be used for frequency regulation in both pumping and generation modes (this has always been available in generating mode). This allows PHES units to absorb power in a more cost-effective manner that not only makes the facility more useful, but also improves the efficiency by approximately 3% [8] and increases the lifetime of the facility. PHES can also be used for peak generation and black starts due to its large power capacity and sufficient discharge time. Finally, PHES provides a load for baseload generating facilities during off-peak production so cycling these units can be avoided, which improves their lifetime as well as their efficiency.

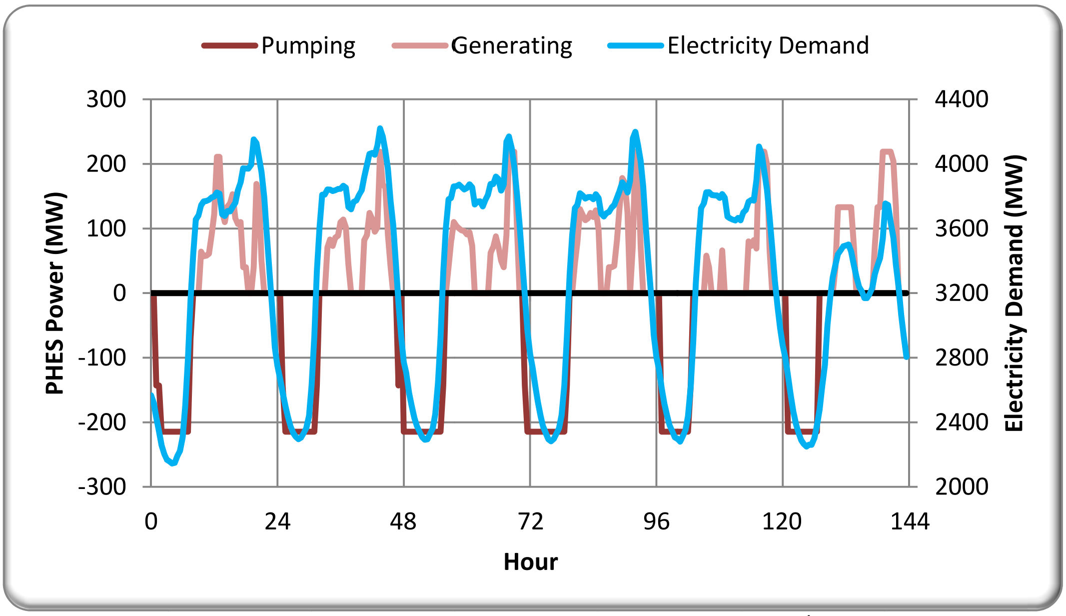


Figure 5-3: Load-levelling by Turlough Hill PHES in Ireland from the 1st to the 6th of October 2007 [20].

5.1.2 Cost

The cost of PHES ranges from $600/kW [2] to upwards of $2,000/kW [8], depending on a number of factors such as size, location, and connection to the power grid.

5.1.3 Disadvantages

In order to make PHES economically viable it is usually constructed on a large scale. Although the cost per kWh of storage is relatively economical in comparison to other techniques, this large-scale necessity results in a very high initial construction cost for the facility, therefore detracting investment in PHES e.g. Bath County storage facility in the United States which has a power capacity of 2,100 MW and cost $1.7 billion in 1985. Due to these design requirements of a PHES facility, the ultimate drawback is its dependence on specific geological formations [21-25]. A suitable site needs two large reservoirs with a sufficient amount of hydraulic head between which are located close enough to enable the construction of a PHES system. However, as well as being rare these geological formations normally exist in remote locations such as mountains, where construction is difficult and the power grid is not present. Although, recent reports illustrate that more suitable sites may exist for PHES than originally anticipated [17, 26-29].

5.1.4 Future

Currently, a lot of work is being carried out to upgrade old PHES facilities with new equipment such as variable speed devices which can increase capacity by 15% to 20%, and efficiency by approximately 3%. This is very popular as energy storage capacity is being developed without the high initial construction costs. Prospects of building new facilities are usually hindered by "high development costs, long lead times and design limitations" [8]. However, even with these issues, there is over 7 GW of new PHES planned within the EU over the next eight years alone [30]. In addition, new methodologies continue to locate more and more suitable PHES sites [17, 26-29]. Therefore, considering the maturity and cost of PHES, it is a very attractive option as an energy storage technology for aiding the integration of fluctuating renewable energy.

5.2 Underground Pumped Hydroelectric Energy Storage (UPHES)

An UPHES facility has the same operating principle as PHES system: two reservoirs with a large hydraulic head between them. The only major difference between the two designs is the locations of their respective reservoirs. In conventional PHES, suitable geological formations must be identified to build the facility, as discussed in section 5.1. However, UPHES facilities have been designed with the upper reservoir at ground level and the lower reservoir deep below the earth's surface. The depth depends on the amount of hydraulic head required for the specific application, see Figure 5-4.

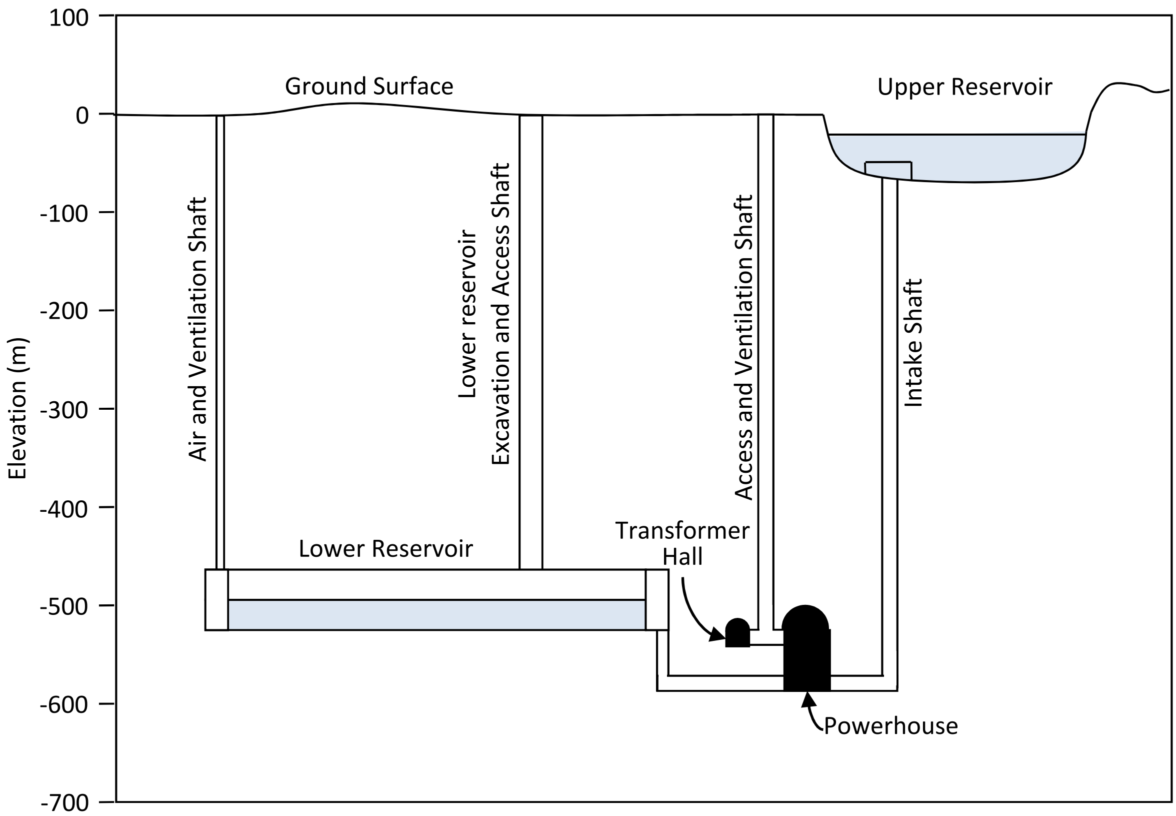


Figure 5-4: Proposed layout of an underground pumped hydroelectric storage facility [18].

5.2.1 Applications

UPHES can provide the same services as PHES: load-levelling, frequency regulation, and peak generation. However, as UPHES does not need to be built on mountainous terrain, it can be constructed in areas which are not as secluded as those for PHES. If economical excavation techniques can be established, then UPHES could be placed anywhere that had enough space for the upper reservoir and hence, it could be positioned in ideal locations for wind farms, the power grid, specific areas of electrical irregularities, etc.

5.2.2 Cost

The capital cost of UPHES is the deciding factor for its future. As it operates in the same way as PHES, it is a very reliable and cost effective storage technique with low maintenance costs. However, depending on the capital costs involved, UPHES might not be a viable option as other technologies begin to develop larger storage capacities e.g. flow batteries. Currently, no costs have been identified for UPHES, primarily due to the lack of facilities constructed. A number of possible cost-saving ideas have been put forward such as using old mines for the lower reservoir of the facility [18, 31]. Also, if something valuable can be removed to make the lower reservoir, it can be sold to make back some of the cost.

5.2.3 Disadvantages

The major disadvantage for UPHES is its commercial youth. To date there is very few, if any, UPHES facilities in operation. Therefore, it is very difficult to analyse the performance of this technology. Currently, there is very little evidence to suggest that economical excavation techniques will be developed in the near future. Consequently, the technical immaturity of UPHES needs to be addressed and typical construction costs defined before it is used as a mainstream energy storage technology.

5.2.4 Future

UPHES could be a viable alternative for energy storage if cost-effective excavation techniques can be identified for its construction. Its relatively large-scale storage capacities, combined with its potential location independence, provide a storage technique with unique characteristics. However, as well as cost, a number of areas need to be investigated further in this area such as its design, power and storage capacities, and its environmental impact to prove it is a viable option. In addition, if more suitable sites are found for conventional PHES, then the desire for UPHES is likely to decline.

5.3 Compressed Air Energy Storage (CAES)

A CAES facility consists of a power train motor that drives a compressor (to compress the air into the cavern), a high pressure turbine (HPT), a low pressure turbine (LPT), and a generator, see Figure 5-5.

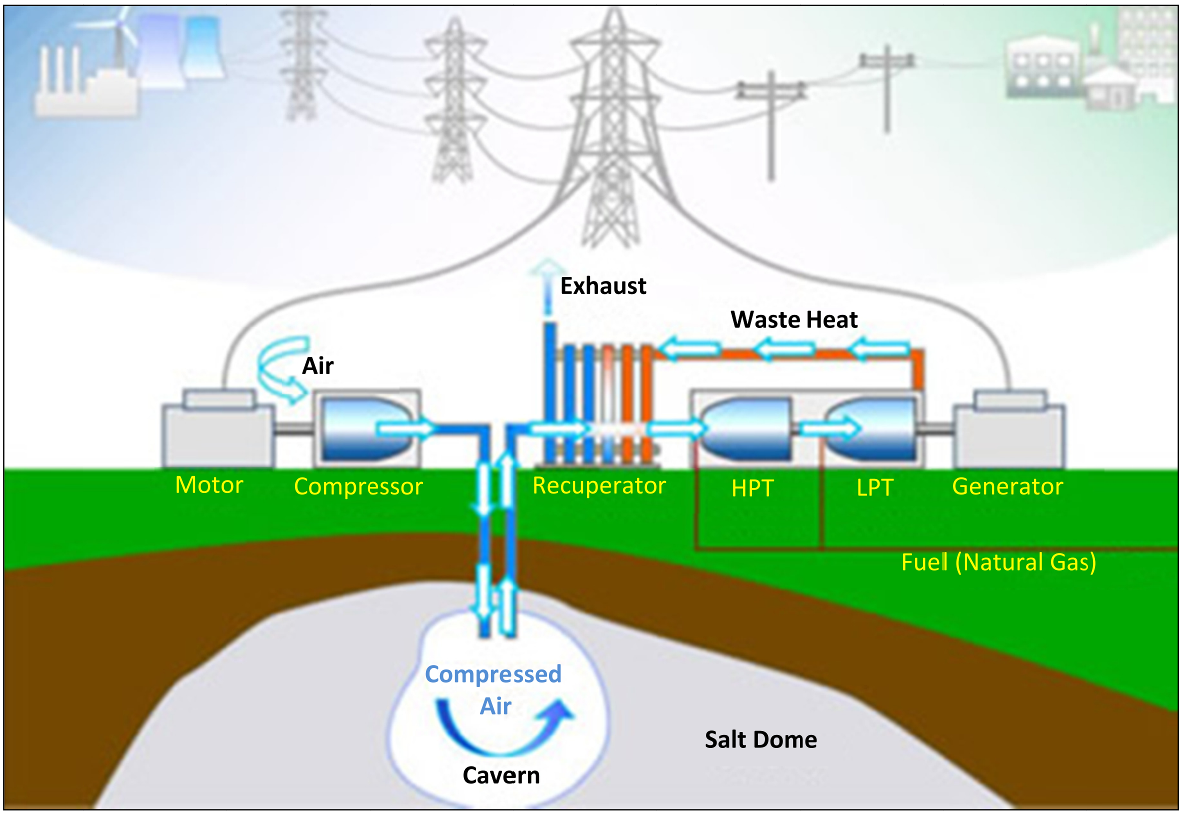


Figure 5-5: Layout of a compressed air energy storage facility [32].

In conventional gas turbines (GT), 66% of the gas used is required to compress the air at the time of generation. Therefore, CAES pre-compresses the air using off-peak electrical power which is taken from the grid to drive a motor (rather than using gas from the GT plant) and stores it in large storage reservoirs. When the GT is producing electricity during peak hours, the compressed air is released from the storage facility and used in the GT cycle. As a result, instead of using expensive gas to compress the air, cheaper off-peak base load electricity is used. Although, when the air is released from the cavern it must be mixed with a small amount of gas before entering the turbine. If there was no gas added, the temperature and pressure of the air would be problematic. If the pressure using air alone was high enough to achieve a significant power output, the temperature of the air would be far too low for the materials and connections to tolerate [1]. The amount of gas required is so small that a GT working simultaneously with CAES can produce three times more electricity than a GT operating on its own, using the same amount of natural gas.

The reservoir can be man-made, but this is expensive so CAES locations are usually decided by identifying natural geological formations that suit these facilities. These include salt caverns, hard-rock caverns, depleted gas fields or an aquifer. Salt caverns can be designed to suit specific requirements. Fresh water is pumped into the cavern and left until the salt dissolves and saturates the fresh water. The water is then returned to the surface and the process is repeated until the required volume cavern is created. This process is expensive and can take up to two years. Hard-rock caverns are even more expensive, usually 60% higher than salt caverns. Finally, aquifers cannot store the air at high pressures and therefore have a relatively lower energy capacity.

CAES uses both electrical energy and natural gas so its efficiency is difficult to quantify. It is estimated that the efficiency of the cycle based on the compression and expansion cycles is in the region of 68% [33] to 75% [8]. Typical plant capacities for CAES are in the region of 50 MW – 300 MW. The life of these facilities is proving to be far longer than existing gas turbines and the charge/discharge ratio is dependent on the size of the compressor used, as well as the size and pressure of the reservoir.

5.3.1 Applications

CAES is the only very large scale storage technique other than PHES. CAES has a fast reaction time with plants usually able to go from 0% to 100% in less than ten minutes, 10% to 100% in approximately four minutes and from 50% to 100% in less than 15 seconds [2]. As a result, it is ideal for acting as a large sink for bulk energy supply and demand and also, it is able to undertake frequent start-ups and shutdowns. Furthermore, traditional GT suffer a 10% efficiency reduction from a 5°C rise in ambient temperatures due a reduction in the air density. CAES use compressed air so they do not suffer from this effect. Also, traditional gas turbines suffer from excessive heat when operating on partial load, while CAES facilities do not. These flexibilities mean that CAES can be used for ancillary services such as frequency regulation, load following, and voltage control [8]. As a result, CAES has become a serious contender in the wind power energy storage market. A number of possibilities are being considered such as integrating a CAES facility with a number of wind farms within the same region. The excess off-peak power from these wind farms could be used to compress air for a CAES facility. *Iowa Association of Municipal Utilities* is currently planning a project of this nature [34].

5.3.2 Cost

The cost of CAES facilities are \$425/kW [2] to \$450/kW [8]. Maintenance is estimated between \$3/kWh [35] and \$10/kWh [36]. Costs are largely dependent on the reservoir construction. Overall, CAES facilities expect to have costs similar to or greater than conventional GT facilities. However, the energy cost is much lower for CAES systems.

5.3.3 Disadvantages

The major disadvantage of CAES facilities is their dependence on geographical location. It is difficult to identify underground reservoirs where a power plant can be constructed, is close to the electric grid, is able to retain compressed air and is large enough for the specific application. As a result, capital costs are generally very high for CAES systems. Also, CAES still uses a fossil fuel (gas) to generate electricity. Consequently, the emissions and safety regulations are similar to conventional gas turbines. Finally, only two CAES facilities currently exist, meaning it is still a technology of potential not experience.

5.3.4 Future

Reservoir developments are expected in the near future due to the increased use of natural gas storage facilities. The US and Europe are more likely to investigate this technology further as they possess acceptable geology for an underground reservoir (specifically salt domes). Due to the limited operational experience, CAES has been considered too risky by many utilities [36].

A number of CAES storage facilities have been planned for the future including:

- 25 MW CAES research facility with an aquifer reservoir in Italy.
- 3 x 100 MW CAES plants in Israel.
- Norton Energy Storage LLC in America is planning a CAES with a limestone mine acting as the reservoir. The first of four phases is expected to produce between 200 MW and 480 MW at a cost of \$50 to \$480 million. The final plant output is planned to be 2,500 MW.

Finally, proposals have also been put forward for a number of similar technologies such as micro CAES and thermal and compressed air storage (TACAS). However, both are in the early stages of development and their future impact is not decisive. Although Joe Pinkerton, CEO of *Active Power,* declared that TACAS "is the first true minute-for-minute alternative to batteries for UPS industry" [8].

5.4 Battery Energy Storage (BES)

There are three important types of large-scale BES. These are:

1. Lead-Acid (LA)
2. Nickel-Cadmium (NiCd)
3. Sodium-Sulphur (NaS)

These operate in the same way as conventional batteries, except on a large scale i.e. two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required.

5.4.1 Lead-Acid (LA) battery

This is the most common energy storage device in use at present. Its success is due to its maturity (research has been ongoing for an estimated 140 years), relatively low cost, long lifespan, fast response, and low self-discharge rate. These batteries are can be used for both short-term applications (seconds) and long-term applications (up to 8 hours).

There are two types of lead-acid (LA) batteries; flooded lead-acid (FLA) and valve regulated lead-acid (VRLA). FLA batteries are made up of two electrodes that are constructed using lead plates which are immersed in a mixture of water (65%) and sulphuric acid (35%), see Figure 5-6. VRLA batteries have the same operating principle as FLA batteries, but they are sealed with a pressure regulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weigh less and occupy less space. However, these advantages are coupled with higher initial costs and shorter lifetime.

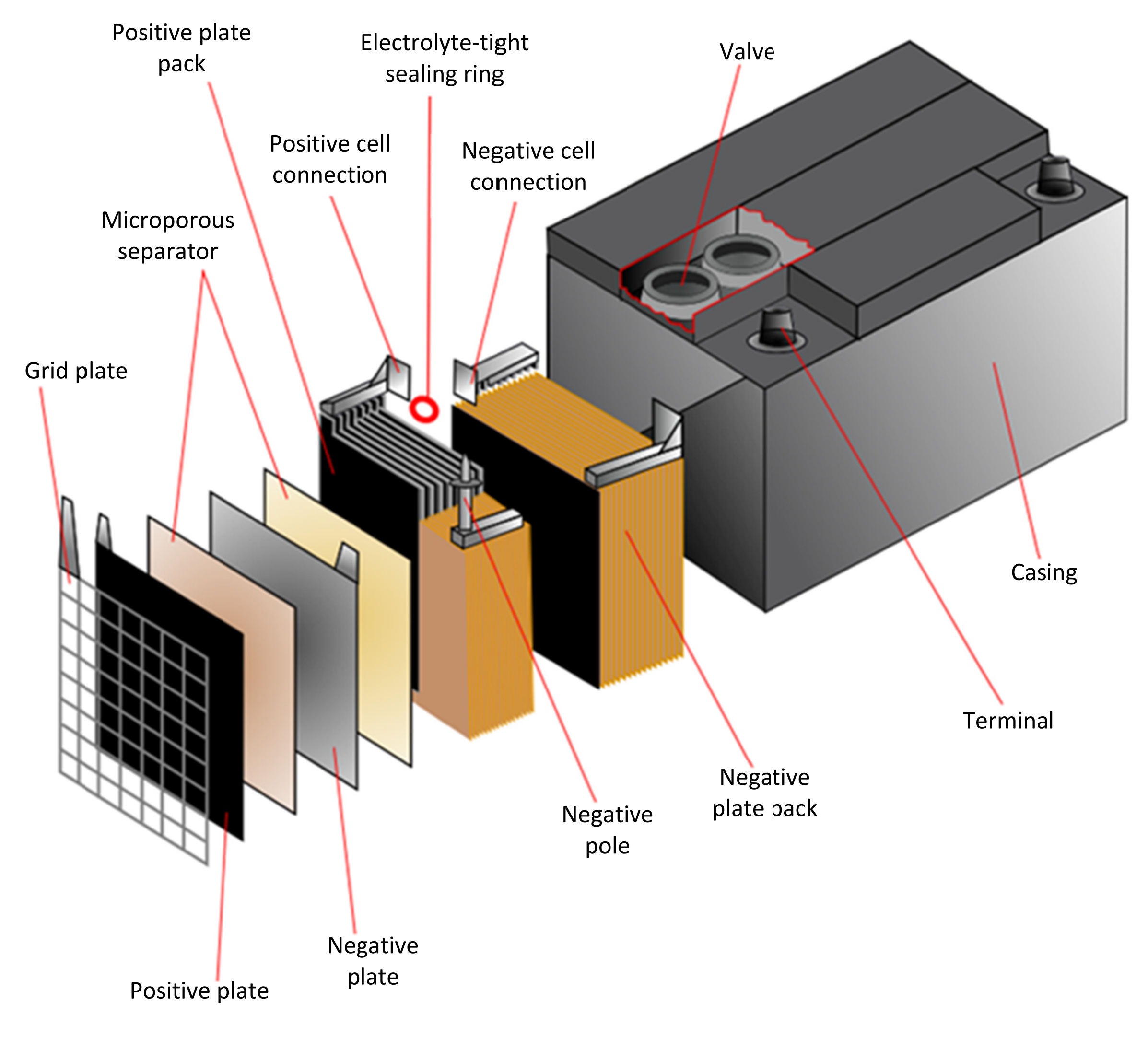


Figure 5-6: Structure of a lead-acid battery [37].

Both the power and energy capacities of lead-acid batteries are based on the size and geometry of the electrodes. The power capacity can be increased by increasing the surface area for each electrode, which means greater quantities of thinner electrode plates in the battery. However, to increase the storage capacity of the battery, the mass of each electrode must be increased, which means fewer and thicker plates. Consequently, a compromise must be met for each application.

LA batteries can respond within milliseconds at full power. The average DC-DC efficiency of a LA battery is 75% to 85% during normal operation, with a life of approximately 5 years or 250-1,000 charge/discharge cycles, depending on the depth-of-discharge [8].

5.4.1.1 Applications

FLA batteries have 2 primary applications [8]:

1. Starting and ignition, short bursts of strong power e.g. car engine batteries
2. Deep cycle, low steady power over a long time

VRLA batteries are very popular for backup power, standby power supplies in telecommunications and also for UPS systems. A number of LA storage facilities are in operation today as can be seen in Table 5-1.

Table 5-1: Details of the largest LA and VRLA battery installations worldwide [2].

				Battery system alone		Total cost of the storage system*	
Plant	Year of installation	Rated Energy (MWh)	Rated Power (MW)	Cost in $1995 ($/kWh)	Cost in $1995 ($/kWh)	Cost in $1995 ($/kWh)	Cost in $1995 ($/kWh)
CHINO California	1988	40	10	201	805	456	1823
HELCO Hawaii (VRLA)	1993	15	10	304	456	777	1166
PREPA Puerto Rico	1994	14	20	341	239	1574	1102
BEWAG Germany	1986	8.5	8.5	707	707	n/a	n/a
VERNON Calif. (VRLA)	1995	4.5	3	305	458	944	1416

* Includes Power Conditioning System and Balance-of-Plant.

5.4.1.2 Cost

Costs for LA battery technology have been stated as $200/kW - $300/kW [2], but also in the region of $580/kW [8]. Looking at Table 5-1 above, the cost variation is evident.

5.4.1.3 Disadvantages

LA batteries are extremely sensitive to their environments. The typical operating temperature for a LA battery is roughly 27°C, but a change in temperature of 5°C or more can cut the life of the battery by 50%. However, if the DoD exceeds this, the cycle life of the battery will also be reduced. Finally, a typical charge-to-discharge ratio of a LA battery is 5:1. At faster rates of charge, the cell will be damaged.

5.4.1.4 Future

Due to the low cost and maturity of the LA battery it will probably always be useful for specific applications. The international *Advanced Lead-Acid Battery Consortium* is also developing a technique to significantly improve storage capacity and also recharge the battery in only a few minutes, instead of the current hours [2]. However, the requirements of new large-scale storage devices would significantly limit the life of a LA battery. Consequently, a lot of research has been directed towards other areas. Therefore, it is unlikely that LA batteries will be competing for future large-scale multi MW applications.

5.4.2 Nickel-Cadmium (NiCd) battery

A NiCd battery is made up of a positive with nickel oxyhydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divider. The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxyhydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery.

There are two NiCd battery designs: sealed (Figure 5-7) and vented (Figure 5-8). Sealed NiCd batteries are the common, everyday rechargeable batteries used in a remote control, lamp etc. No gases are released from these batteries, unless a fault occurs. Vented NiCd batteries have the same operating principles as sealed ones, but gas is released if overcharging or rapid discharging occurs. The oxygen and hydrogen are released through a low-pressure release valve making the battery safer, lighter, more economical, and more robust than sealed NiCd batteries.

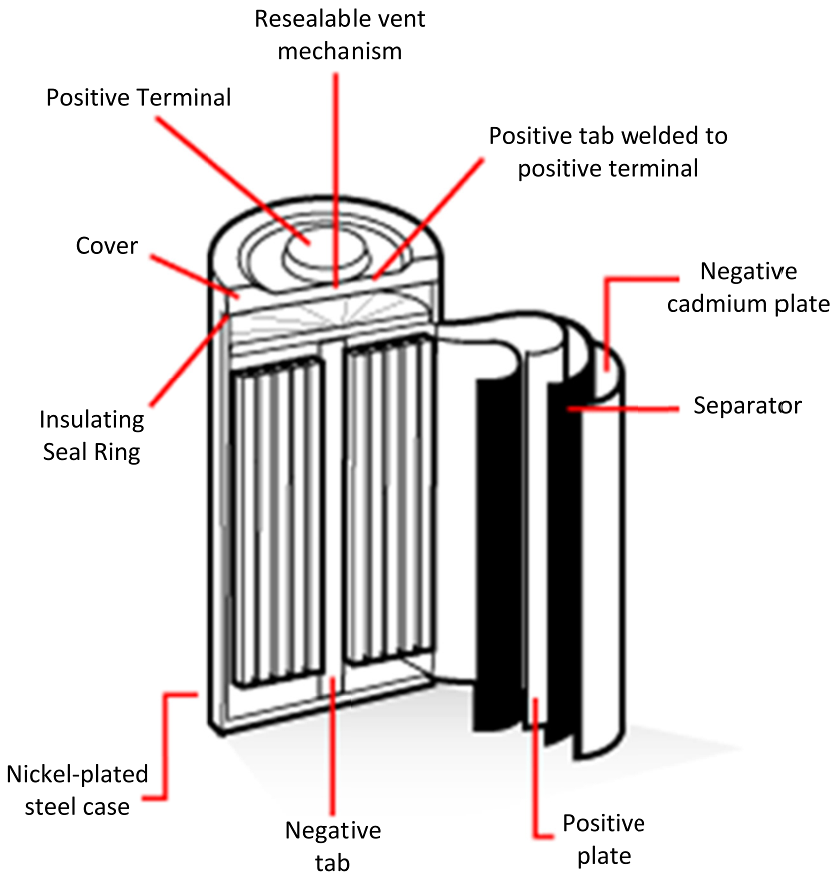


Figure 5-7: Structure of a sealed nickel-cadmium battery [38, 39].

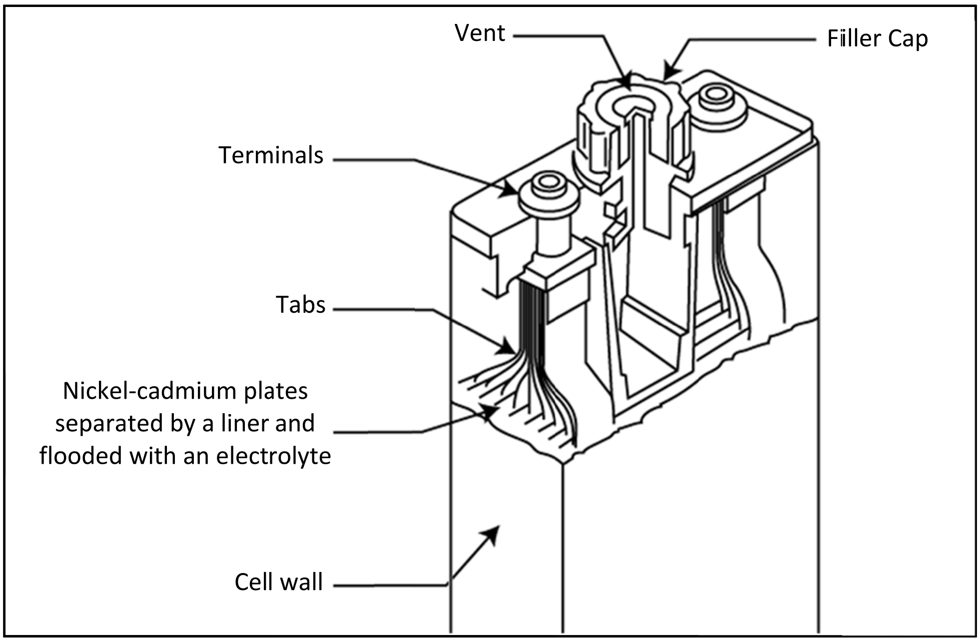


Figure 5-8: Structure of a vented nickel-cadmium cell [40, 41].

The DC-DC efficiency of a NiCd battery is 60%-70% during normal operation although the life of these batteries is relatively high at 10 to 15 years, depending on the application. NiCd batteries with a pocket-plate design have a life of 1,000 charge/discharge cycles, and batteries with sintered electrodes have a life of 3,500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds. At small DoD rates (approximately 10%) NiCd batteries have a much longer cycle life (50,000 cycles) than other batteries such as LA batteries. They can also operate over a much wider temperature range than LA batteries, with some able to withstand occasional temperatures as high as 50°C.

5.4.2.1 Applications

Sealed NiCd batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented NiCd batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical [8]. NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures. However, they do not perform well during peak shaving applications, and consequently are generally avoided for energy management systems.

5.4.2.2 Cost

NiCd batteries cost more than LA batteries at $600/kW [8]. However, despite the slightly higher initial cost, NiCd batteries have much lower maintenance costs due to their environmental tolerance.

5.4.2.3 Disadvantages

Like LA batteries, the life of NiCd batteries can be greatly reduced due to the DoD and rapid charge/discharge cycles. However, NiCd batteries suffer from 'memory' effects and also lose more energy during due to self-discharge standby than LA batteries, with an estimated 2% to 5% of their charge lost per month at room temperature in comparison to 1% per month for LA batteries [8]. Also, the environmental effects of NiCd batteries have become a widespread concern in recent years as cadmium is a toxic material. This creates a number of problems for disposing of the batteries.

5.4.2.4 Future

It is predicted that NiCd batteries will remain popular within their current market areas, but like LA batteries, it is unlikely that they will be used for future large-scale projects. Although just to note, a 40 MW NiCd storage facility was constructed in Alaska; comprising of 13,760 cells at a cost of $35M [2]. The cold temperatures experienced were the primary driving force behind the use NiCd as a storage medium. NiCd will probably remain more expensive than LA batteries, but they do provide better power delivery. However, due to the toxicity of cadmium, standards and regulations for NiCd batteries will continue to rise.

5.4.3 Sodium-Sulphur (NaS) Battery

NaS batteries have three times the energy density of LA, a longer life span, and lower maintenance. These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten-sulphur positive electrode. The electrolyte used is solid β-alumina. During discharging, sodium ions pass through the β-alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide, see Figure 5-9. During charging, the reaction is reversed so that the sodium polysulfide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally insulated enclosure that must keep it above 270°C, usually at 320°C to 340°C.

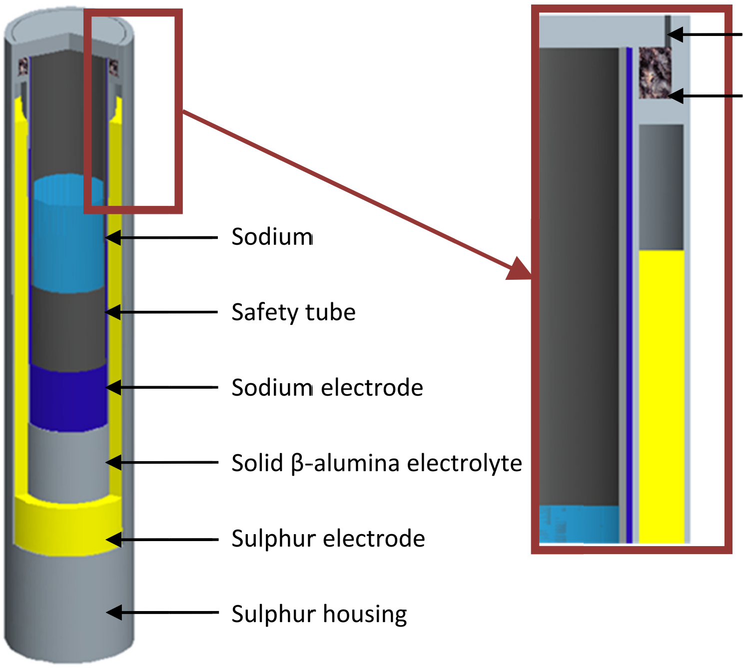


Figure 5-9: Structure of a sodium-sulphur cell.

A typical NaS module is 50 kW at 360 kWh or 50 kW at 430 kWh. The average round-trip energy efficiency of a NaS battery is 86% [2] to 89% [8]. The cycle life is much better than for LA or NiCd batteries. At 100% DoD, the NaS batteries can last approximately 2,500 cycles. As with other batteries, this increases as the DoD decreases; at 90% DoD the unit can cycle 4,500 times and at 20% DoD 40,000 times [8].

5.4.3.1 Applications

One of the greatest characteristics of NaS batteries is its ability to provide power in a single, continuous discharge or else in shorter larger pulses (up to five times higher than the continuous rating). It is also capable of pulsing in the middle of a long-term discharge. This flexibility makes it very advantageous for numerous applications such as energy management and power quality. NaS batteries have also been used for deferring transmission upgrades.

5.4.3.2 Cost

Currently, NaS batteries cost $810/kW, but it is only a recently commercialised product. This cost is likely to be reduced as production increases, with some predicting reductions upwards of 33% [8].

5.4.3.3 Disadvantages

The major disadvantage of NaS batteries is retaining the device at elevated temperatures above 270°C. It is not only energy consuming, but it also brings with it problems such as thermal management and safety regulations [42]. Also, due to harsh chemical environments, the insulators can be a problem as they slowly become conducting and self-discharge the battery.

5.4.3.4 Future

A 6 MW, 8 h unit has been built by *Tokyo Electric Power Company* (TEPCO) and *NGK Insulators, Ltd.*, (NGK), in Tokyo, Japan with an overall plant efficiency of 75% and is thus far proving to be a success, see Figure 5-10. The materials required to create a NaS battery are inexpensive and abundant, and 99% of the battery is recyclable. The NaS battery has the potential to be used on a MW scale by combining modules. Combining this with its functionality to mitigate power disturbances, NaS batteries could be a viable option for smoothing the output from wind turbines into the power grid [8]. *American Electric Power* is planning to incorporate a 6 MW

NaS battery with a wind farm for a two year demonstration [43, 44]. The size of the wind farm has yet to be announced, but the results from this will be pivotal for the future of the NaS battery with renewable energy.

Figure 5-10: A 6 MW, 8 h sodium-sulphur energy storage facility in Tokyo, Japan [2].

5.5 Flow Battery Energy Storage (FBES)

There are three primary types of FBES:

1. Vanadium-Redox (VR)
2. Polysulphide-Bromide (PSB)
3. Zinc-Bromine (ZnBr)

They all operate in a similar fashion; two charged electrolytes are pumped to the cell stack where a chemical reaction occurs, allowing current to be obtained from the device when required. The operation of each will be discussed in more detail during the analysis.

5.5.1 Vanadium-Redox (VR) Flow Battery

A VR battery is made up of a cell stack, electrolyte tank system, control system and a PCS (see Figure 5-11). These batteries store energy by interconnecting two forms of vanadium ions in a sulphuric acid electrolyte at each electrode; with V^{2+}/ V^{3+} in the negative electrode, and V^{4+}/ V^{5+} in the positive electrode. The size of the cell stack determines the power capacity (kW) whereas the volume of electrolyte (size of tanks) indicates the energy capacity (kWh) of the battery.

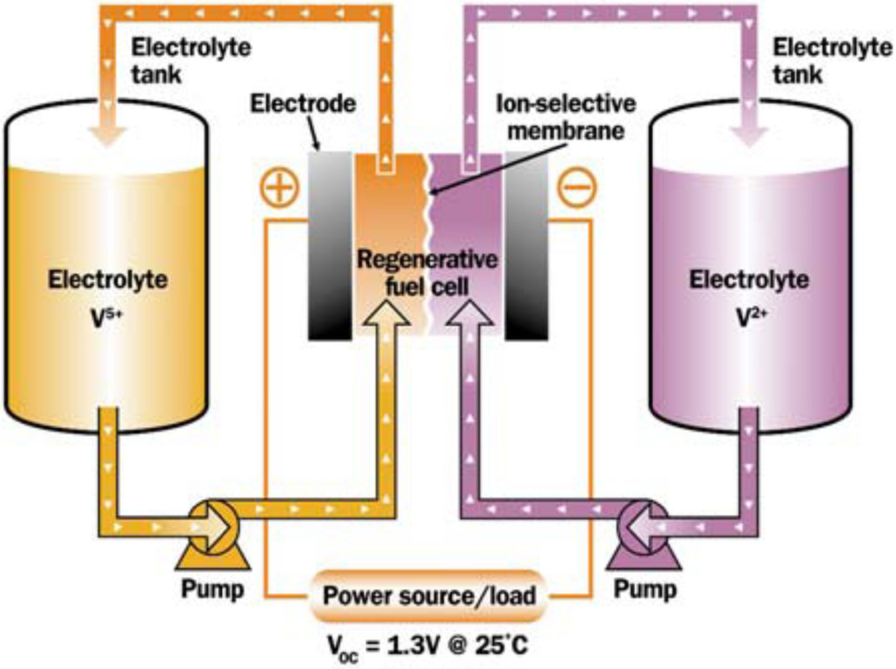


Figure 5-11: Structure of a vanadium-redox flow battery [45].

As the battery discharges, the two electrolytes flow from their separate tanks to the cell stack where H^+ ions are passed between the two electrolytes through the permeable membrane. This process induces self-separation within the solution thus changing the ionic form of the vanadium as the potential energy is converted to electrical energy. During recharge this process is reversed. VR batteries operate at normal temperature with an efficiency as high as 85% [2] and [8]. As the same chemical reaction occurs for charging and discharging, the charge/discharge ratio is 1:1. The VR battery has a fast response, from charge to discharge in 0.001 s and also a high overload capacity with some claiming it can reach twice its rated capacity for several minutes [2]. VR batteries can operate for 10,000 cycles giving them an estimated life of 7-15 years depending on the application. Unlike conventional batteries they can be fully discharged without any decline in performance [46]. At the end of its life (10,000 cycles), only the cell stack needs to be replaced as the electrolyte has an indefinite life and thus can be reused. VR batteries have been designed as modules so they can be constructed on-site.

5.5.1.1 Applications

As the power and energy capacities are decoupled, the VR flow battery is a very versatile device in terms of energy storage. It can be used for every energy storage requirement including UPS, load levelling, peak-shaving, telecommunications, electric utilities and integrating renewable resources. Although the versatility of flow batteries makes it extremely useful for a lot of applications, there are a number of competing devices within each area that perform better for their specific application. Consequently, although capable of performing for numerous applications, VR batteries are only considered where versatility is important, such as the integration of renewable resources.

Table 5-2: Sumitomo Electric Industries Ltd. vanadium-redox battery project experience [47]

Location	Application	Ratings	Operation
Kaskima Kita Power Stations, Japan	Load levelling	200 kW x 4 h	1996
Sumitomo Densetsu Co. Ltd.	Load levelling	100 kW x 8 h	Feb 2001
The Institute of Applied Energy	Stabilisation of wind turbine output	170 kW x 6 h	Mar 2001
Tottori SANYO Electric Co., Ltd.	Power quality (voltage sag compensation) and load levelling	1500 kW x 1 h (3000 kW x 1.5 s)	Apr 2001
Obayashi Corp. (Dunlop Golf Course)	Solar PV storage (DC only)	30 kW x 8 h	Apr 2001
Kwansei Gakuin University	Peak shaving	500 kW x 10 h	Jul 2001
CESI, Italy	Peak shaving	42 kW x 2 h	Nov 2001
Tomamac Wind Villa	Wind turbine output stabilization and storage	4000 kW x 90 min	2005

5.5.1.2 Cost

There are two costs associated with flow batteries: the power cost (kW), and the energy cost (kWh), as they are independent of each other. The power cost for VR batteries is $1,828/kW, and the energy cost is $300/kWh to $1,000/kWh, depending on system design [8].

5.5.1.3 Disadvantages

VR batteries have the lowest power density and require the most cells (each cell has a voltage of 1.2 V) in order to obtain the same power output as other flow batteries. For smaller-scale energy applications, VR batteries are very complicated in relation to conventional batteries, as they require much more parts (such as pumps, sensors, control units) while providing similar characteristics. Consequently, when deciding between a flow battery and a conventional battery, a decision must be made between a simple but constrained device (conventional battery), and a complex but versatile device (flow battery).

5.5.1.4 Future

VR batteries have a lot of potential due to their unique versatility, specifically their MW power and storage capacity potential. However, the commercial immaturity of VR batteries needs to be changed to prove it is a viable option in the future.

5.5.2 Polysulphide-Bromide (PSB) Flow Battery

PSB batteries operate very similarly to VR batteries. The unit is made up of the same components; a cell stack, electrolyte tank system, control system and a PCS (see Figure 5-12). The electrolytes used within PSB flow batteries are sodium bromide as the positive electrolyte, and sodium polysulphide as the negative electrolyte. During discharge, the two electrolytes flow from their tanks to the cell where the reaction takes place at a polymer membrane that allows sodium ions to pass through. Like VR batteries, self-separation occurs during the discharge process and as before, to recharge the battery this process is simply reversed. The voltage across each cell is approximately 1.5 V.

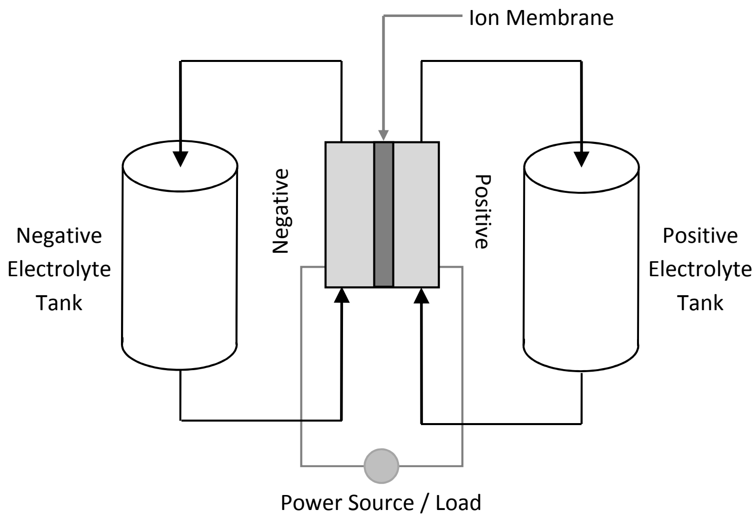


Figure 5-12: Structure of a polysulphide-bromide flow battery [8].

PSB batteries operate between 20°C and 40°C, but a wider range can be used if a plate cooler is used in the system. The efficiency of PSB flow batteries approaches 75% according to [2] and [8]. As with VR batteries, the discharge ratio is 1:1, since the same chemical reaction is taking place during charging and discharging. The life expectancy is estimated at 2,000 cycles but once again, this is very dependent on the application. As with VR batteries the power and energy capacities are decoupled in PSB batteries.

5.5.2.1 Applications

PSB flow batteries can be used for all energy storage requirements including load levelling, peak shaving, and integration of renewable resources. However, PSB batteries have a very fast response time; it can react within 20 milliseconds if electrolyte is retained charged in the stacks (of cells). Under normal conditions, PSB batteries can charge or discharge power within 0.1 s [2]. Therefore, PSB batteries are particularly useful for frequency response and voltage control.

5.5.2.2 Cost

The power capacity cost of PSB batteries is $1,094/kW and the energy capacity cost is $185/kWh [8].

5.5.2.3 Disadvantages

During the chemical reaction small quantities of bromine, hydrogen, and sodium sulphate crystals are produced. Consequently, biweekly maintenance is required to remove the sodium-sulphate by-products. Also, two companies designed and planned to build PSB flow batteries. *Innogy's Little Barford Power Station* in the UK wanted to use a 24,000 cell 15 MW 120 MWh PSB battery, to support a 680 MW combined cycle gas turbine plant. Tennessee Valley Authority (TVA) in Columbus wanted a 12 MW, 120 MWh to avoid upgrading the network. However, both facilities have been cancelled with no known explanation.

5.5.2.4 Future

Like the VR battery, PSB batteries can scale into the MW region and therefore must have a future within energy storage. However, until a commercial demonstration succeeds, the future of PSB batteries will remain doubtful.

5.5.3 Zinc-Bromine (ZnBr) Flow Battery

These flow batteries are slightly different to VR and PSB flow batteries. Although they contain the same components: a cell stack, electrolyte tank system, control system, and a PCS (see Figure 5-13), ZnBr flow batteries do not operate in the same way.

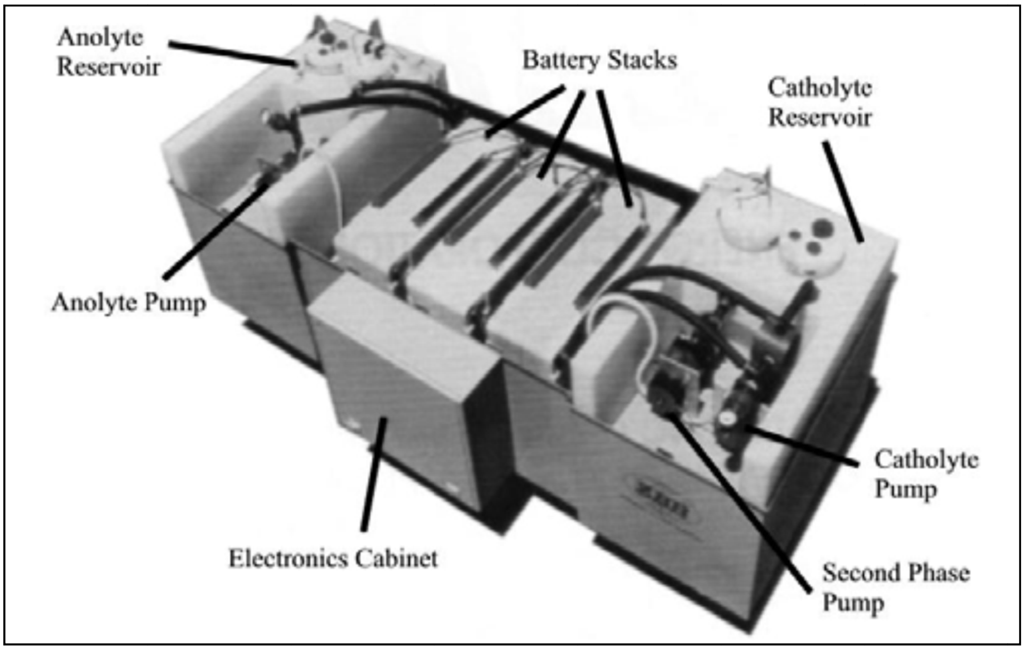


Figure 5-13: Structure of a zinc-bromine flow battery [48].

During charging the electrolytes of zinc and bromine ions (that only differ in their concentration of elemental bromine) flow to the cell stack. The electrolytes are separated by a microporous membrane. Unlike VR and PSB flow batteries, the electrodes in a ZnBr flow battery act as substrates to the reaction. As the reaction occurs, zinc is electroplated on the negative electrode and bromine is evolved at the positive electrode, which is somewhat similar to conventional battery operation. An agent is added to the electrolyte to reduce the reactivity of the elemental bromine. This reduces the self-discharge of the bromine and improves the safety of the entire system [48]. During discharge the reaction is reversed; zinc dissolves from the negative electrode and bromide is formed at the positive electrode. ZnBr batteries can operate in a temperature range of 20°C to 50°C. Heat must be removed by a small chiller if necessary. No electrolyte is discharged from the facility during operation and hence the electrolyte has an indefinite life. The membrane however, suffers from slight degradation during the operation, giving the system a cycle life of approximately 2,000 cycles. The ZnBr battery can be 100% discharged without any detrimental consequences and suffers from no memory effect. The efficiency of the system is about 75% [2] or 80% [8]. Once again, as the same reaction occurs during charging and discharging, the charge/discharge ratio is 1:1, although a slower rate is often used to increase efficiency [8]. Finally, the ZnBr flow battery has the highest energy density of all the flow batteries, with a cell voltage of 1.8 V.

5.5.3.1 Applications

The building block for ZnBr flow batteries is a 25 kW, 50 kWh module constructed from three 60-cell battery stacks in parallel, each with an active cell area of 2500 sq. cm [48]. ZnBr batteries also have a high energy density of 75 Wh/kg to 85 Wh/kg. As a result, the ZnBr batteries are relatively small and light in comparison to other conventional and flow batteries such as LA, VR and PSB. Consequently, ZnBr is currently aiming at the renewable energy backup market. It is capable of smoothing the output fluctuations from a wind farm [2], or a solar panel [48], as well as providing frequency control. Installations currently completed have used ZnBr flow batteries for UPS, load management and supporting microturbines, solar generators, substations and T&D grids [2].

5.5.3.2 Cost

The power capacity cost is $639/kW and the energy capacity cost is $400/kWh [8].

5.5.3.3 Disadvantages

It is difficult to increase the power and storage capacities into the large MW ranges as the modules cannot be linked hydraulically, hence the electrolyte is isolated within each module. Modules can be linked electrically though and plans indicate that systems up to 1.5 MW are possible. As stated the membrane suffers from slight degradation during the reaction so it must be replaced at the end of the batteries life (2,000 cycles).

5.5.3.4 Future

The future of ZnBr batteries is currently aimed at the renewable energy market. *Apollo Energy Corporation* plan to develop a 1.5 MW ZnBr battery to back up a 20 MW wind farm for several minutes. They hope to keep the wind farm operational for an additional 200+ hours a year [2]. The results from this will be very decisive for the future of ZnBr flow batteries.

5.6 Flywheel Energy Storage (FES)

A FES device is made up of a central shaft that holds a rotor and a flywheel. This central shaft rotates on two magnetic bearings to reduce friction, see Figure 5-14. These are all contained within a vacuum to reduce aerodynamic drag losses. Flywheels store energy by accelerating the rotor/flywheel to a very high speed and maintaining the energy in the system as kinetic energy. Flywheels release energy by reversing the charging process so that the motor is then used as a generator. As the flywheel discharges, the rotor/flywheel slows down until eventually coming to a complete stop.

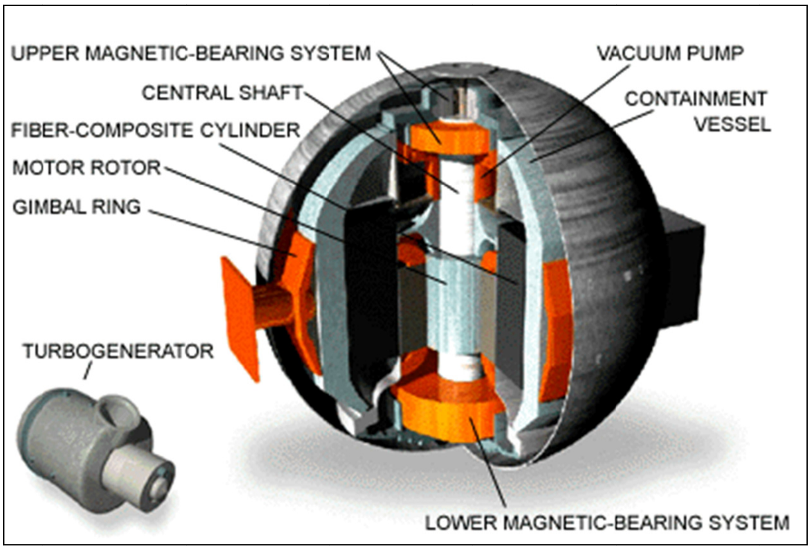


Figure 5-14: Components of a flywheel energy storage device [49].

The rotor dictates the amount of energy that the flywheel is capable of storing. Flywheels store power in direct relation to the mass of the rotor, but to the square of its surface speed. Consequently, the most efficient way to store energy in a flywheel is to make it spin faster, not by making it heavier. The energy density within a flywheel is defined as the energy per unit mass:

$$\frac{E_{KINETIC}}{m_f} = \frac{1}{2} v_{CIRCULAR}^2 = \frac{\sigma}{\rho} \tag{3}$$

Where:

$E_{KINETIC}$ = total kinetic energy in Joules (J)

m_f = mass of the flywheel in kg

$v_{CIRCULAR}$ = the circular velocity of the flywheel in m/s^2

σ = the specific strength of the material in Nm/kg

ρ = density of the material in kg/m^3

The power and energy capacities are decoupled in flywheels. In order to obtain the required power capacity, you must optimise the motor/generator and the power electronics. These systems, referred to as ‘low-speed flywheels’, usually have relatively low rotational speeds, approximately 10,000 rpm and a heavy rotor made form steel. They can provide up to 1650 kW, but for a very short time, up to 120 s.

To optimise the storage capacities of a flywheel, the rotor speed must be increased. These systems, referred to as ‘high-speed flywheels’, spin on a lighter rotor at much higher speeds, with some prototype composite flywheels claiming to reach speeds in excess of 100,000 rpm. However, the fastest flywheels commercially available spin at about 80,000 rpm. They can provide energy up to an hour, but with a maximum power of 750 kW.

Over the past number of years, the efficiency of flywheels has improved up to 80% [8], although some sources claim that it can be as high as 90% [1]. As it is a mechanical device, the charge-to-discharge ratio is 1:1.

5.6.1 Applications

Flywheels have an extremely fast dynamic response, a long life, require little maintenance, and are environmentally friendly. They have a predicted lifetime of approximately 20 years or tens of thousands of cycles. As the storage medium used in flywheels is mechanical, the unit can be discharged repeatedly and fully without any damage to the device. Consequently, flywheels are used for power quality enhancements such as Uninterruptable Power Supply (UPS), capturing waste energy that is very useful in electric vehicle applications and finally, to dampen frequency variation, making FES very useful to smooth the irregular electrical output from wind turbines.

5.6.2 Cost

At present, FES systems cost between \$200/kWh to \$300/kWh for low-speed flywheels, and \$25,000/kWh for high-speed flywheels [2]. The large cost for high-speed flywheels is typical for a technology in the early stages of development. Battery technology such as the lead-acid battery is the main competitor for FES. These have similar characteristics to FES devices, and usually cost 33% less [8]. However, as mentioned previously (see section 3.7.1), FES have a longer lifespan, require lower maintenance, have a faster charge/discharge, take up less space and have fewer environmental risks [2].

5.6.3 Disadvantages

As flywheels are optimised for power or storage capacities, the needs of one application can often make the design poorly suited for the other. Consequently, low-speed flywheels may be able to provide high power capacities but only for very short time period, and high-speed flywheels the opposite. Also, as flywheels are kept in a vacuum during operation, it is difficult to transfer heat out of the system, so a cooling system is usually integrated with the FES device. Finally, FES devices also suffer from the idling losses: when flywheels are spinning on standby, energy is lost due to external forces such as friction or magnetic forces. As a result, flywheels need to be pushed to maintain its speed. However, these idling losses are usually less than 2%.

5.6.4 Future

Low maintenance costs and the ability to survive in harsh conditions are the core strengths for the future of flywheels. Flywheels currently represent 20% of the \$1 billion energy storage market for UPS. Due to its size and cycling capabilities, FES could establish even more within this market if consumers see beyond the larger initial investment. As flywheels require a preference between optimisation of power or storage capacity, it is unlikely to be considered a viable option as a sole storage provider for power generation applications. Therefore, FES needs to extend into applications such as regenerative energy and frequency regulation where it is not currently fashionable if it is to have a future [8].

5.7 Supercapacitor Energy Storage (SCES)

Capacitors consist of two parallel plates that are separated by a dielectric insulator, see Figure 5-15. The plates hold opposite charges which induces an electric field, in which energy can be stored. The energy within a capacitor is given by

$$E = \frac{1}{2} C V^2 \tag{4}$$

where E is the energy stored within the capacitor (in Joules), V is the voltage applied, and C is the capacitance found from [1]

$$C = \frac{A}{d} \varepsilon_r \varepsilon_0 \tag{5}$$

where A is the area of the parallel plates, d is the distance between the two plates, ε_r is the relative permittivity or dielectric constant, and ε_0 is the permittivity of free space (8.854 x 10^{-12} F/m). Therefore, to increase the energy stored within a capacitor, the voltage or capacitance must be increased. The voltage is limited by the maximum Energy Field strength (after this the dielectric breaks down and starts conducting), and the capacitance depends on the dielectric constant of the material used.

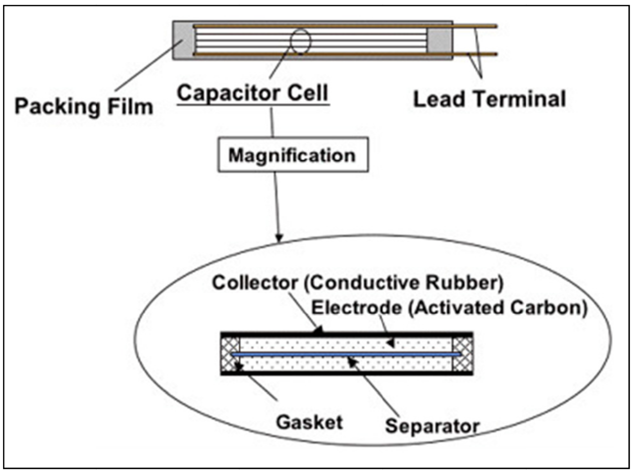


Figure 5-15: Components of a supercapacitor energy storage device [50].

Supercapacitors are created by using thin film polymers for the dielectric layer and carbon nanotube electrodes. They use polarised liquid layers between conducting ionic electrolyte and a conducting electrode to increase the capacitance. They can be connected in series or in parallel. SCES systems usually have energy densities of 20 MJ/m^3 to 70 MJ/m^3, with an efficiency of 95% [2].

5.7.1 *Applications*

The main attraction of SCES is its fast charge and discharge, combined with its extremely long life of approximately 1 x 10^6 cycles. This makes it a very attractive replacement for a number of small-scale (<250 kW) power quality applications. In comparison to batteries, supercapacitors have a longer life, do not suffer from memory effect, show minimal degradation due to deep discharge, do not heat up, and produce no hazardous substances [1]. As a result, although the energy density is smaller, SCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load levelling tasks. SCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to one minute [2].

5.7.2 Cost

SCES costs approximately $12,960/kWh [2] to $28,000/kWh [1]. Therefore, large scale applications are not economical using SCES.

5.7.3 Disadvantages

SCES has a very low energy storage density leading to very high capital costs for large scale applications. Also, they are heavier and bulkier than conventional batteries.

5.7.4 Future

Despite the small energy storage densities on offer, the exceptional life and cycling capabilities, fast response and good power capacity (up to 1 MW) of supercapacitors means that they will always be useful for specific applications. However, it is unlikely that SCES will be used as a sole energy storage device. One long-term possibility involves combining SCES with a battery based storage system. SCES could smooth power fluctuations, and the battery provides the storage capacity necessary for longer interruptions. However, other technologies (such as flow batteries) are more likely to be developed for such applications. As a result, the future of SCES is likely to remain within specific areas that require a lot of power, very fast, for very short periods.

5.8 Superconducting Magnetic Energy Storage (SMES)

A SMES device is made up of a superconducting coil, a power conditioning system, a refrigerator and a vacuum to keep the coil at low temperature, see Figure 5-16.

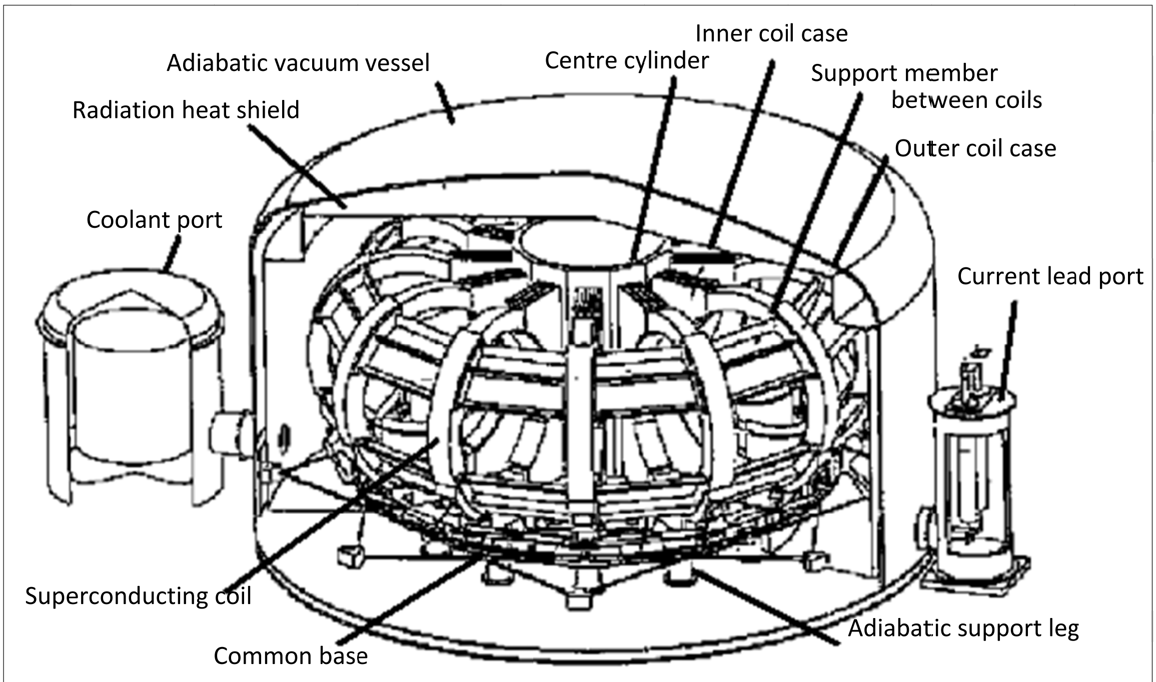


Figure 5-16: Components of a superconducting magnetic energy storage device [2].

Energy is stored in the magnetic field created by the flow of direct current in the coil wire. In general, when current is passed through a wire, energy is dissipated as heat due to the resistance of the wire. However, if the wire used is made from a superconducting material such as lead, mercury or vanadium, zero resistance occurs, so energy can be stored with practically no losses. In order to obtain this superconducting state within a material, it must be kept at a very low temperature. There are two types of superconductors; low-temperature superconductors that must be cooled from 0 K to 7.2 K, and high-temperature superconductors that have a temperature range of 10 K to 150 K, but are usually in the 100±10K region. The energy stored within the coil (in Joules), E_C, can be obtained from [1]

$$E_C = \frac{1}{2} L I^2 \quad (6)$$

where L is the inductance of the coil, and I is the current passing through it. Therefore, material properties are extremely important as temperature, magnetic field, and current density are pivotal factors in the design of SMES.

The overall efficiency of SMES is in the region of 90% [35] to 99% [8]. SMES has very fast discharge times, but only for very short periods of time, usually taking less than one minute for a full discharge. Discharging is possible in milliseconds if it is economical to have a PCS that is capable of supporting this. Storage capacities for SMES can be anything up to 2 MW, although its cycling capability is its main attraction. SMES devices can run for thousands of charge/discharge cycles without any degradation to the magnet, giving it a life of 20+ years.

5.8.1 Applications

Due to the high power capacity and instantaneous discharge rates of SMES, it is ideal for the industrial power quality market. It protects equipment from rapid momentary voltage sags, and it stabilises fluctuations within the entire network caused by sudden changes in consumer demand levels, lightening strikes or operation switches. As a result, SMES is a very useful network upgrade solution with some sources claiming that it can improve the capacity of a local network by up to 15% [8]. However, due to high energy consumption of the refrigeration system, SMES is unsuitable for daily cycling applications such as peak reduction, renewable applications, and generation and transmission deferral [2].

5.8.2 Cost

SMES cost approximately \$300/kW [2] to \$509/kW [8]. It is worth noting that it is difficult to compare the cost of SMES to other storage devices due to its scales and purpose. In practical terms SMES should be compared to other network upgrade solutions where it is often very competitive or even less costly. Finally, the cost of storing electricity within a superconductor is expected to decline by almost 30% which could make SMES an even more attractive option for network improvements [8].

5.8.3 Disadvantages

The most significant drawback of SMES is its sensitivity to temperature. As discussed the coil must be maintained at an extremely low temperature in order to behave like a superconductor. However, a very small change in temperature can cause the coil to become unstable and lose energy. Also, the refrigeration can cause parasitic losses within the system. Finally, although the rapid discharge rates provide some unique applications for SMES, it also limits its applications significantly. As a result, other multifunctional storage devices such as batteries are usually more attractive.

5.8.4 Future

Immediate focus will be in developing small SMES devices in the range of 1 MW to 10 MW for the power quality market which has foreseeable commercial potential. A lot of work is being carried out to reduce the capital and operating costs of high-temperature SMES devices, as it is expected to be the commercial superconductor of choice once manufacturing processes are more mature, primarily due to cheaper cooling. There is a lot of market potential for SMES due to its unique application characteristics, primarily in transmission upgrades and industrial power quality [8]. However, one of the greatest concerns for SMES is its reliability over a long period of time.

5.9 Hydrogen Energy Storage System (HESS)

HESS is the first of the three energy storage systems discussed in this report. HESS is the one of the most immature but also one of the most promising energy storage techniques available. As an energy storage system, HESS acts as a bridge between all three major sectors of an energy system: the electricity, heat and transport sectors. It is the only energy storage system that allows this level of interaction between these sectors and hence it is becoming a very attractive option for integrating large quantities of intermittent wind energy. There are three stages in HESS:

1. Create hydrogen
2. Store hydrogen
3. Use hydrogen (for required application)

5.9.1 Create Hydrogen

There are three primary techniques to create hydrogen:

1. Extraction from Fossil Fuels
2. Reacting steam with methane
3. Electricity (Electrolysis)

However, as producing hydrogen from fossil fuels is four times more expensive than using the fuel itself, and reacting steam with methane produces pollutants, electrolysis has become the most promising technique for hydrogen production going forward.

An electrolyser uses electrolysis to breakdown water into hydrogen and oxygen. The oxygen is dissipated into the atmosphere and the hydrogen is stored so it can be used for future generation. Due to the high cost of electrical production, only a small proportion of the current hydrogen production originates from electrolysis. Therefore, the most attractive option for future production is integrating electrolyser units with renewable resources such as wind or solar. In order to achieve this, an electrolyser must be capable of operating:

1. with high efficiency
2. under good dynamic response
3. over a wide input range
4. under frequently changing conditions [2]

Recently a number of advancements have been made including higher efficiencies of 85%, wider input power capabilities, and more variable inputs. A new Proton Exchange Membrane (PEM) has been developed instead of the preceding alkaline membranes. This can operate with more impure hydrogen, faster dynamic response, lower maintenance, and increased suitability for pressurisation [2]. However, a PEM unit has lower efficiency (40% - 60%) so some development is still required.

Electrolysers are modular devices so the capacity of a device is proportional to the number of cells that make up a stack. The largest commercial systems available can produce 485 Nm^3/h, corresponding to an input power of 2.5 MW. The lifetime of an electrolyser is proving difficult to predict due to its limited experience. However, research has indicated that the electrolyser unit will have the shortest lifespan within HESS. Some have predicted a lifespan in the region of 5-10 years but this is only an estimate [2].

5.9.1.1 Cost

The estimated costs to produce power using an electrolyser are extremely varied. Predictions are as low as €300/kW [51] up to €1,100/kW [2]. *ITM Power* in the UK claim to have produced an electrolyser that can operate with renewable sources, at a cost of $164/kW, and are currently planning to begin mass production in 2008 [52]. Maintenance costs are expected to be 3% of the capital cost [2].

5.9.1.2 Future

Immediate developments are investigating the possibility of producing an electrolyser that can pressurise the hydrogen during electrolysis, as compressing the hydrogen after production is expensive and unreliable. Like all areas of HESS, the electrolyser needs a lot more development as well as technical maturity.

5.9.2 Store Hydrogen

A number of different options are currently available to store hydrogen:

1. Compression: The hydrogen can be compressed into containers or underground reservoirs. The cost of storing hydrogen in pressure vessels is $11/kWh to $15/kWh [2]. However, for underground reservoirs it is only $2/kWh [53]. This is a relatively simple technology, but the energy density and efficiency (65% to 70%) are low. Also, problems have occurred with the mechanical compression. However, this is at present the most common form of hydrogen storage for the transport industry, with the hydrogen compressed to approximately 700 bar (the higher the storage pressure, the higher the energy density, see Figure 5-17). Although the energy required for the compression is a major drawback.

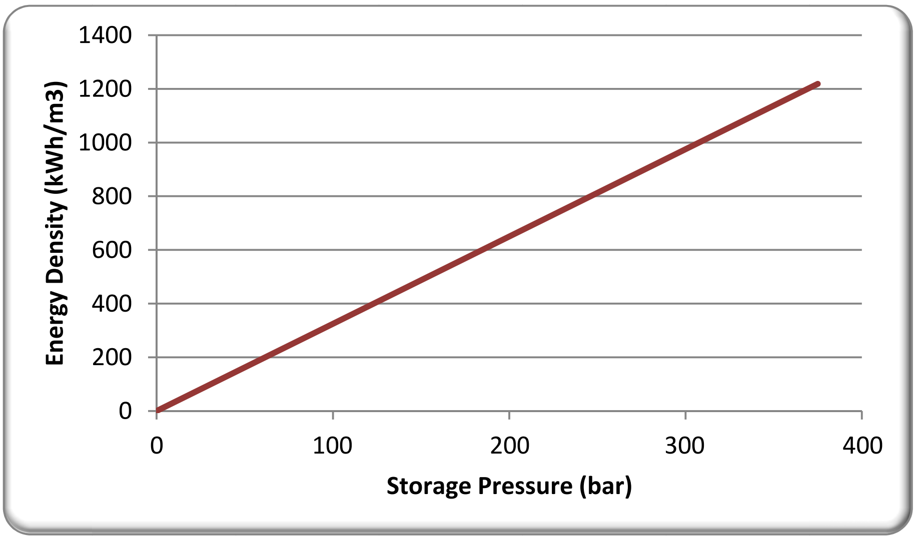


Figure 5-17: Energy density vs. pressure for a hydrogen gas storage [2].

2. Liquefied Hydrogen: The hydrogen can be liquefied by pressurising and cooling. Although the energy density is improved, it is still four times less than conventional petrol. Also, keeping the hydrogen liquefied is very energy intensive, as it must be kept below 20.27K [54]
3. Metal Hydrides: Certain materials absorb molecular hydrogen such as nanostructured carbons and clathrate hydrate. By absorbing the hydrogen in these materials, it can be easily transported and stored. Once required, the hydrogen is removed from the parent material. The energy density is similar to that obtained for liquefied hydrogen [54]. The extra material required to store the hydrogen is a major problem with this technique as it creates extra costs and mass. This is still a relatively new technology, so with extra development it could be a viable option; especially if the mass of material is reduced. Carbon-based absorption can achieve higher energy densities but it has higher costs and even less demonstrations [2]. Both metal-hydride or carbon-based absorption use thermal energy. This thermal heat could be got from the waste heat of other processes with HESS, such as the electrolyser or fuel cell, to improve overall efficiency.

Each storage technique is in the early stages of development and hence there is no optimum method at present with research being carried out in each area.

5.9.3 Use Hydrogen

There are two superior ways of using hydrogen:

1. Internal Combustion Engine (ICE)
2. Fuel Cell (FC)

It is expected that the ICE will act as a transition technology while fuel cells are improving, because the modifications required to convert an ICE to operate on hydrogen are not very significant. However, the FC, due to its virtually emission-free, efficient and reliable characteristics, is expected to be the generator of choice for future hydrogen powered energy applications.

5.9.3.1 Fuel Cell

A fuel cell converts stored chemical energy, in this case hydrogen, directly into electrical energy. A fuel cell consists of two electrodes that are separated by an electrolyte, see Figure 5-18.

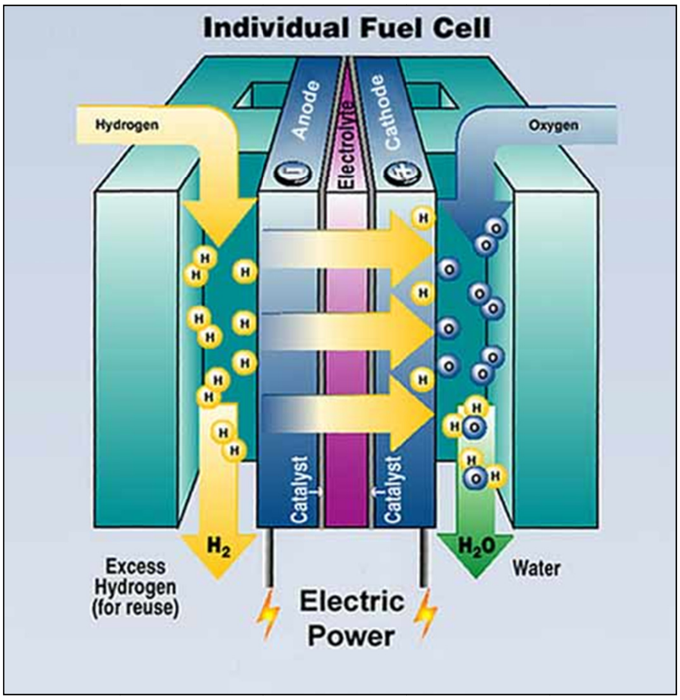


Figure 5-18: Structure of a fuel cell [55].

Hydrogen is passed over the anode (negative) and oxygen is passed over the cathode (positive), causing hydrogen ions and electrons to form at the anode. The electrons flow through an external circuit to produce electricity, whilst the hydrogen ions pass from the anode to the cathode. Here the hydrogen ions combine with oxygen to produce water. The energy produced by the various types of cells depends on the operation temperature, the type of fuel cell, and the catalyst used; see Table 5-3. Fuel cells do not produce any pollutants and have no moving parts. Therefore, theoretically it should be possible to obtain a reliability of 99.9999% in ideal conditions [56].

5.9.3.2 Cost

All fuel cells cost between €500/kW and €8,000/kW which is very high, but typical of an emerging technology [2]. These costs are expected to reduce as the technology ages and commercialisation matures.

5.9.3.3 Future

Immediate objectives for fuel cells include harnessing the waste heat more effectively to improve co-generation efficiency and also, combining fuel cells with electrolysers as a single unit. The advantage being lower capital costs although resulting in lower efficiency and increased corrosion [2]. Fuel cells are a relatively new technology with high capital costs. However, with characteristics such as no moving parts, no emissions, lightweight, versatility and reliability, this is definitely a technology with a lot of future potential.

Table 5-3: Properties of the various fuel cell technologies currently available [1].

Fuel Cell	Electrolyte	Catalyst	Efficiency (%)	Operating temp (°C)	Power output (kW)	Applications	Additional notes
Alkaline Fuel Cell (AFC)	Potassium Hydroxide	Platinum	70	150 - 200	0.3 - 12	Widely used in the space industry (NASA)	Water produced by cell is drinkable. Can be easily poisoned by carbon dioxide (CO_2)
Polymer Electrolyte Membrane **or** Proton Exchange Membrane (PEM)	Solid Organic Polymer	Platinum	45	80	50 - 250	Portable applications such as cars	Cell is sensitive to impurities so hydrogen used must be good quality
Phosphoric Acid Fuel Cell (PAFC)	Phosphoric Acid	Platinum	40	150 - 200	200	Large stationary generation. Also Co-generation (increases efficiency to 85%)	Can use impure hydrogen such as hydrogen from fossil fuels
Molten Carbonate Fuel Cell (MCFC)	Potassium, Sodium or Lithium Carbonate	Variety of non-precious metals	60	650	10 – 2000	Co-generation (increases efficiency to 85%)	High operating temperature and corrosive electrolyte result in short cell lifetime
Solid Oxide Fuel Cells (SOFC)	Solid Zirconium Oxide	Variety of non-precious metals	60	1000	100	Utility applications. Prototype for Co-generation exists (85% efficient)	High temperature causes slow start-up

5.9.4 *Disadvantages*

The primary disadvantage with hydrogen is the huge losses due to the number of energy conversions required. Typically in a system that has high wind energy penetrations, by the time that hydrogen is actually being used for its final purpose it has gone through the following processes with corresponding efficiencies: 1) Hydrogen is created by electrolysis – 85% efficient, 2) the hydrogen is stored – 65% to 70% efficient, 3) hydrogen is consumed in a fuel cell car, power plant, or CHP unit – efficiency of 40% to 80%. This results in an overall efficiency ranging from 22% to 48%. In addition, this process assumes only one storage stage within the life of the hydrogen where as typically more than one storage stage would be necessary i.e. stored when created, and stored at the location of use. Therefore, by implementing a "hydrogen economy", the efficiency of the system is very low that could result in very high energy costs and very poor utilisation of limited resources such as wind or biomass. In summary, although the hydrogen energy storage system offers huge flexibility, this flexibility is detrimental to the overall energy system efficiency.

5.9.5 *Future of HESS*

The use of hydrogen within the transport and electricity generation industries is expected to grow rapidly as electrolysis, storage techniques, and fuel cells become more commercially available.

There are very ambitious hydrogen programs in the EU, US, and Japan, indicating increasing interest in hydrogen technology. Iceland is attempting to become the first 'hydrogen country' in the world by producing hydrogen from surplus renewable energy and converting its transport infrastructure from fossil fuels to hydrogen. In Norway, *Statkraft* plans to connect an electrolysis unit to a large wind turbine and *Norsk Hydro* is continuing a project to provide Utsira Island with a wind-hydrogen system. In Germany, *Siemens* and *P&T Technologies* are developing a wind-hydrogen engine using an ICE. In the UK *Wind Hydrogen Limited* intend to develop large scale wind-hydrogen schemes. Finally, *HyGen* in California is developing a multi megawatt hydrogen generating and distributing network [2].

Car manufacturers are driving research in hydrogen for both the transport and infrastructure divisions. The automotive industry has engaged in setting up a strategy for the introduction of hydrogen to the transport sector with a number of single prototype projects advancing to fleet demonstrations [2].

Hydrogen is a serious contender for future energy storage due to its versatility. Once hydrogen can be produced effectively, it can be used for practically any application required. Consequently, producing hydrogen from renewable resources using electrolysis is currently the most desirable objective available. Primarily due to the versatility and potential of hydrogen to replace conventional fuel, "It is envisaged that the changeover to a hydrogen economy is less than fifty years from now" [2].

5.10 Thermal Energy Storage (TES)

Thermal energy storage involves storing energy in a thermal reservoir so that it can be recovered at a later time. A number of thermal applications are used instead of electricity to provide heating and cooling including Aquifer Thermal Storage (ATS), and Duct Thermal Storage (DTS). However, these are heat generation techniques rather than energy storage techniques and therefore will not be discussed in detail here. In terms of storing energy, there are two primary thermal energy storage options. The first option is a technology which is used to supplement air conditioning in buildings and is displayed in Figure 5-19. The second option is an energy storage system rather than a technology which will be discussed in more detail later.

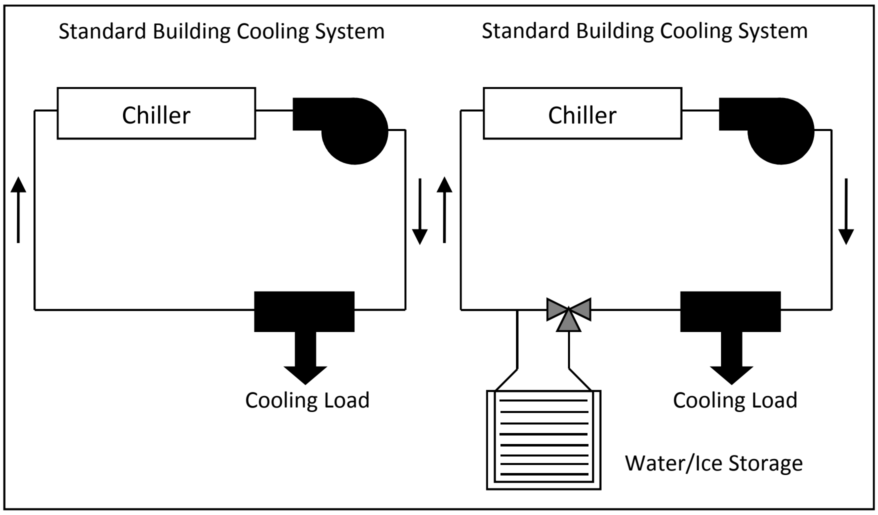


Figure 5-19: Structure of an air-conditioning thermal energy storage unit [8].

5.10.1 Air-Conditioning Thermal Energy Storage (ACTES)

The Air-Conditioning Thermal Energy Storage (ACTES) units work with the air conditioning in buildings by using off-peak power to drive the chiller to create ice. During the day, this ice can be used to provide the cooling load for the air conditioner. This improves the overall efficiency of the cycle as chillers are much more efficient when operated at night time due to the lower external temperatures. Also, if ACTES units are used, the size of the chiller and ducts can be reduced. Chillers are designed to cope with the hottest part of the hottest day possible, all day. Therefore, they are nearly always operating below full capacity. If ACTES facilities are used, the chiller can be run at full capacity at night to make the ice and also at full capacity during the day; with the ice compensating for shortfalls in the chiller capacity. ACTES units lose approximately 1% of their energy during storage [8].

5.10.1.1 Cost

If ACTES is installed in an existing building, it costs from $250 to $500 per peak kW shifted, and it has a payback period from one to three years. However, if installed during construction, the cost saved by using smaller ducts (20% to 40% smaller), chillers (40% to 60% smaller), fan motors, air handlers and water pumps will generally pay for the price of the ACTES unit. As well as this, the overall air conditioning cost is reduced by 20% to 60% [8].

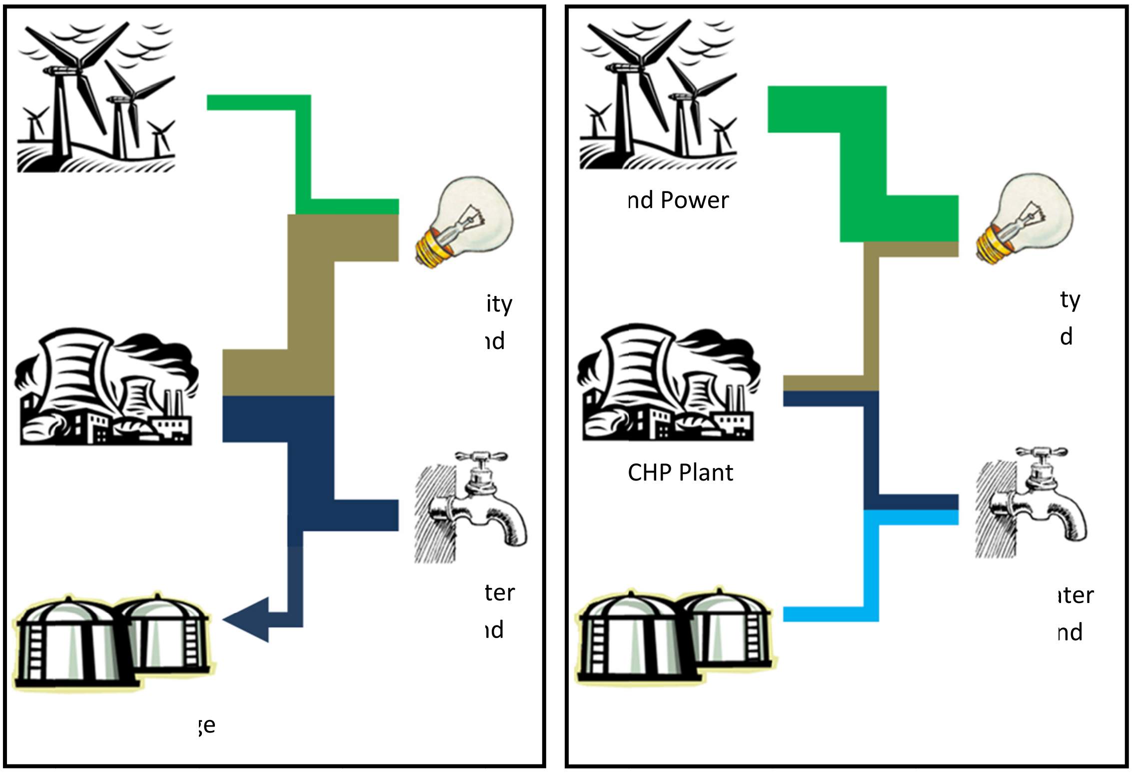
5.10.1.2 Future

Due to the number of successful installations that have already occurred, this technology is expected to grow significantly where air-conditioning is a necessity. It is however, dependent on the future market charges that apply, as this technology benefits significantly from cheaper off-peak power and demand charges. Finally, ACTES units will have to compete with other building upgrades such as lighting and windows, for funding in the overall energy saving strategies enforced [8].

5.10.2 Thermal Energy Storage System (TESS)

The thermal energy storage system can also be used very effectively to increase the flexibility within an energy system. As mentioned previously in this report, by integrating various sectors of an energy system, increased wind penetrations can be achieved due to the additional flexibility created. Unlike the hydrogen energy storage system which enabled interactions between the electricity, heat and transport sectors, thermal energy storage only combines the electricity and heat sectors with one another. By introducing district heating into an energy system, then electricity and heat can be provided from the same facility to the energy system using Combined Heat and Power (CHP) plants. This brings additional flexibility to the system which enables larger penetrations of intermittent renewable energy sources. To illustrate the flexibility induced by thermal energy storage on such a system, a snapshot of the power during different scenarios is presented below. The system in question contains a CHP plant, wind turbines, a thermal storage, a hot water demand, and an electrical demand as illustrated in Figure 5-20.

During times of low wind power, a lot of electricity must be generated by the CHP plants to accommodate for the shortfall power production. As a result, a lot of hot water is also being produced from the CHP plant as seen in Figure 5-20a. The high production of hot water means that production is now greater than demand, and consequently, hot water is sent to the thermal storage. Conversely, at times of high wind power, the CHP plants produce very little electricity and hot water. Therefore, there is now a shortage in of hot water so the thermal storage is used to supply the shortfall, as seen in Figure 5-20b.



(a) **(b)**

Figure 5-20: Thermal energy storage system during (a) a low wind scenario and (b) a high wind scenario.

This system has been put into practice in Denmark which has the highest wind penetration in the world. Also, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system [57].

5.10.2.1 Disadvantages

Similar to the hydrogen energy storage system, the primary disadvantage with a thermal energy storage system is the large investments required to build the initial infrastructure. However, the thermal energy storage system has two primary advantages: 1) the overall efficiency of the energy system is improved with the implementation of a TESS. CHP production is approximately 85% to 90% efficiecnt while conventional power plants are only 40% efficient, and 2) this technique has already been implemented in Denmark so it is a proven solution. On the negative side, as stated previously, thermal energy storage does not improve flexibility within the transport sector like the hydrogen energy storage system, but this is inferior to the advantages it possesses. Therefore, in summary, the thermal energy storage system does have disadvantages, but these are small in comparison to the advantages.

5.10.2.2 Future

Due to the efficiency improvements and maturity of this system, it is very likely that it will become more prominent throughout the world. Not only does it enable the utilisation of more intermittent renewable energy (such as wind), but it also maximises the use of fuel within power plants, something that will become critical as biomass becomes more prominent. This system has been put into practice in Denmark which has the highest wind penetration in the world. In addition, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system at a lower cost than a conventional energy system [57]. Therefore, it is evident this technology can play a crucial role in future energy systems.

5.11 Electric Vehicles (EVs)

The final energy storage system that will be discussed in this report is the implantation of electric vehicles. Once again, system flexibility and hence feasible wind penetrations are increased with the introduction of electric vehicles into the transport sector. As illustrated in Figure 20, electric vehicles can feed directly from the power grid while stationary, at individual homes or at common recharging points, such as car parks or recharging stations. By implementing electric vehicles it is possible to make large-scale battery energy storage economical, combat the huge oil dependence `within the transport sector and drastically increase system flexibility (by introducing the large-scale energy storage) [58]. Consequently, similar to the HESS and the TESS, electric vehicles also provide a method of integrating existing energy systems more effectively.

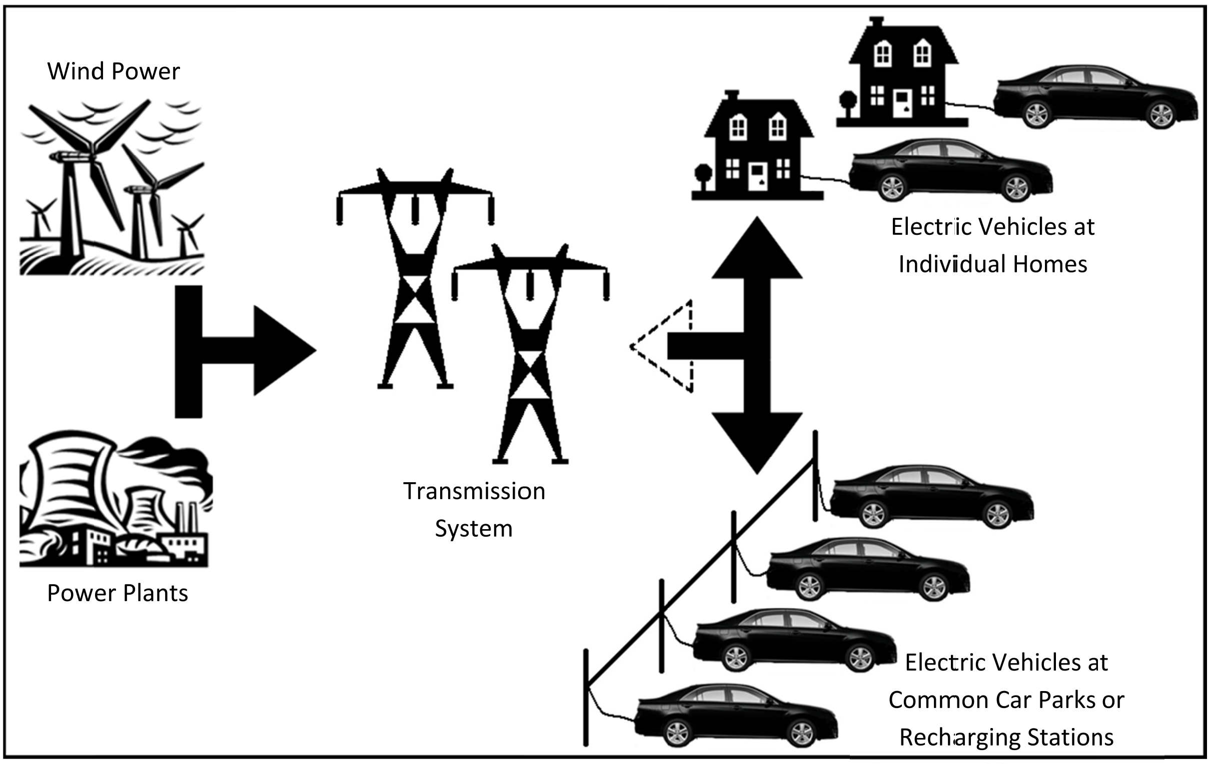


Figure 5-21: Schematic of electric vehicles interacting with the electric power grid.

5.11.1 Applications

Electric vehicles can be classified under three primary categories: Battery Electric Vehicles (BEV), Smart Electric Vehicles (SEV), and Vehicle to Grid (V2G). BEVs are plugged into the electric grid and act as additional load. In contrast, SEVs have the potential to communicate with the grid. For example, at times of high wind production, it is ideal to begin charging electric vehicles to avoid ramping centralised production. In addition, at times of low wind production, charging vehicles should be avoided if possible until a later stage. V2G electric vehicles operate in the same way as SEVs, however, they have the added feature of being able to supply power back to the grid. This increases the level of flexibility within the system once again. All three types of electric vehicles could be used to improve wind penetrations feasible on a conventional grid, with each advancement in technology increasing the wind penetrations feasible from approximately 30% to 65% [58] (from BEV to V2G).

5.11.2 Cost

The costs associated with electric vehicles are different to the costs quoted for other storage technologies. Consumers are not buying electric vehicles to provide energy storage capacity for the grid, instead they are buying electric vehicles as a mode of transport. Therefore, it is difficult to compare the costs of electric vehicles under the conventional \$/kW and \$/kWh that other storage systems are compared with. As a result, below is a comparison between the price of electric vehicles and conventional vehicles, as this comparison is more relevant when considering the uptake of electric vehicles. Figure 21 illustrated the cost of owning a BEV and a conventional electric vehicle over a 105,000 km lifetime, with 25% of its life in urban areas. It is evident from Figure 21 that BEVs are approximately 20% more expensive than conventional vehicles: while SEVs and V2G would be even more expensive but these are still at the development stage. As SEVs and V2G electric vehicles will enable significantly larger wind penetrations on the power grid that BEVs [58], it is likely that economic incentives will be necessary to attract consumers to purchase SEV and V2G vehicles.

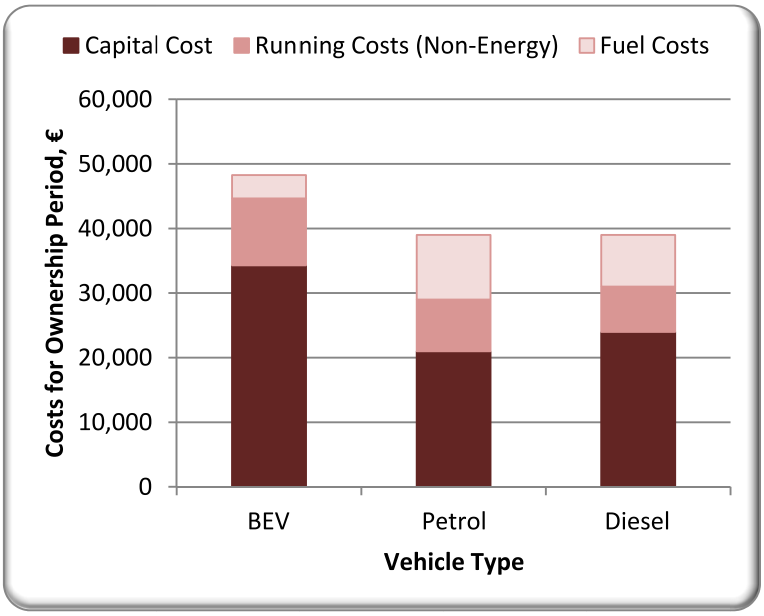


Figure 5-22: Cost of battery electric and conventional vehicles over a lifetime of 105,000 km (25% urban driving) [59].

5.11.3 Disadvantages

The primary disadvantage with electric vehicles is the initial investment to establish the required infrastructure. Transmission lines will need to be upgraded to allow for high power capacities to and (in the case of V2G) from the electric cars, battery banks or charging stations will be required to replace conventional refuelling stations, and maintenance services will need to be established as we transfer from conventional internal combustion engines to electric motors. In addition, travelling habits may need to be altered due to the alternative limitations associated with electric vehicles instead of conventional vehicles, such as driving styles and time required for refuelling. Finally, the remaining issue with electric vehicles is the driving range that can be obtained. Currently, hydrogen vehicles have a much larger range than electric vehicles, although hydrogen vehicles are much less efficient. Therefore, depending on which of these factors is more important for different energy systems will most likely decide which of these technologies is preferred.

5.11.4 Future

Electric vehicles are most likely going to be a key component in a number of future energy systems with large penetrations of intermittent renewable energy. This is primarily due to the two advantages mentioned in the introduction to this section: they reduce oil dependence and provide affordable large-scale energy storage. However, as mentioned already, alternative options such as hydrogen vehicles may reduce the attraction to electric vehicles within energy systems which prioritise range over energy efficiency.

6 Energy Storage Comparison

As outlined in section 4, energy storage can be utilised for a broad range of applications. However, the type of technology which is suitable for these is applications, is primarily defined by their potential power and storage capacities that can be obtained. From section 5 it was clear that each energy storage facility is capable of different power and storage capacities. Therefore, to provide a fair comparison between the various energy storage technologies, they have been grouped together based on the size of power and storage capacity that they can achieve. Four categories have been created: devices with large power (>50 MW) and storage (>100 MWh) capacities; devices with medium power (1-50 MW) and storage capacities (5-100 MWh); devices with small power (<10 MW) and storage capacities (<10 MWh); and finally, a section on energy storage systems. These are energy storage technologies that will be discussed along with their corresponding categories:

1. PHES
2. UPHES
3. CAES

Large Power and Storage Capacities

4. BES
5. FBES

Medium Power and Storage Capacities

6. FES
7. SCES
8. SMES

Small Power and Storage Capacities

9. HESS
10. TESS
11. EVs

Energy Storage Systems

Below there is an initial comparison of the remaining storage technologies within the first three categories defined above. This is followed by an overall comparison across all of these categories. The HESS, TESS, and EVs have unique characteristics as these are energy systems i.e. they require a number of different technologies which can be controlled differently. As a result, these have not been included in the comparison below. Instead, they are discussed briefly after the comparison in general terms rather than with specific figures. A separate more-detailed study has been carried out using a complete energy system analysis tool called EnergyPLAN [60], to begin evaluating the implications of these systems [61, 62].

6.1 Large power and energy capacities

The only devices identified in this report capable of large power (>50 MW) and energy capacities (>100 MWh) are PHES, UPHES and CAES.

New PHES facilities are unlikely to be built as upgrades continue to prove successful. Once upgrades have been completed on existing PHES facilities, the potential for PHES will depend heavily on the availability of suitable sites like all other large-scale energy storage technologies. It is widely believed that there are a limited number of suitable sites remaining for PHES. Although, recent studies completed have illustrated the potential for seawater PHES [17, 29] as well as the potential for many more freshwater PHES sites than originally anticipated [26-28]. Therefore, if results continue in this fashion, PHES may only be constrained by economics and not technical feasibility, indicating that it could become a very important technology as fuel prices continue to rise in the future.

In theory UPHES could be a major contender for the future as it operates under the same operating principals as PHES: therefore, almost all of the technology required to construct such a facility is already available and at a very mature stage. In addition, sites for UPHES will not be dependent on locations in mountainous areas like PHES, which could be advantageous as there are often isolated regions where construction is difficult and expensive. However, UPHES will still have unique site constraints of its own as it will require a suitable underground reservoir. Until such time that an extensive investigation is completed analysing the availability of such reservoirs, the future of UPHES will remain uncertain.

Finally, the attractiveness of CAES depends on the price and availability of gas as well as the potential for suitable locations. It is a flexible, reliable, and efficient technology but it still needs gas to operate. CAES by its nature is capital intensive and hence a long-term commitment is required (~30 years) when constructing this technology. Therefore, if the energy system considering CAES has long term ambitions to eliminate a dependence on gas, due to price, security of supply, etc., then this should be accounted for when analysing the feasibility of CAES. Also, although vessels can be used for the compressed air, underground storage reservoirs are usually required to make CAES an economical alternative. Consequently, like PHES and UPHES, the potential for CAES will also depend heavily on the availability of suitable locations.

In conclusion, it is evident that large-scale energy storage facilities all share one key issue: the availability of suitable locations. However, based on recent studies, suitable sites for PHES may be more prominent than originally anticipated, which gives PHES a significant advantage especially in an Irish context. However, one other key consideration is the maturity of the various technologies. UPHES and CAES utilising vessels are still only concepts and thus unproven. CAES using underground reservoirs is often considered a mature technology as there are currently only two facilities operating worldwide. In comparison, there is over 90 GW of PHES (at over 240 facilities) currently in operation as well as 7 GW of additional plants planned in Europe alone over the next eight years [30]. Based on the potential availability of sites and the maturity of PHES, it is most likely large-scale energy storage technology feasible, especially for the Irish energy system.

6.2 Medium power and energy capacities

This section includes BES and FBES. The only major contender from the BES storage technologies for future large-scale projects is the NaS battery. LA and NiCd will probably be used for their existing applications, but further breakthroughs are unlikely. FBES technologies (including VR, PSB and ZnBr) are all currently competing in the renewable energy market. Demonstration results for these batteries will be decisive for their future. It is worth noting that flow batteries are much more complex than conventional batteries. This is the reason conventional batteries still remain an attractive alternative. Conventional batteries are simple, but constrained (power and storage capacities are coupled) while flow batteries are flexible, but complex (power and storage capacities are independent, but a number of extra parts are required). The other key issue for this category will be the development of electric vehicles. If technological advancements continue within electric vehicles, then stand-alone battery energy storage may could be replaced by distributed batteries in EVs. Therefore, the future of this sector is very uncertain as various technologies continue to develop. Future demonstration projects for NaS, FBES, and EVs will all play a decisive role in defining the future of this sector.

6.3 Small power capacities and storage capacities

FES, SCES and SMES primarily differ in terms of the power capacity which can be achieved, as their storage capabilities are generally less than one hour. FES is used for the smallest power requirements (typically up to 750 kW), SCES for medium power (up to 1 MW), and SMES for large power issues (up to 10 MW). The optimum technology depends on the power required for the specific application being considered. Due to the unique ratio of their capacities, these technologies are likely to be used for their specific purposes such as uninterruptable power supply and ancillary service, well into the future. However, they are unlikely to be utilised as a core technology for the large-scale integration of fluctuating renewable energy.

6.4 Overall comparison of energy storage technologies

It is very difficult to compare the various types of energy storage techniques to one another as they are individually ideal for certain applications but no technology is perfect for everything. Consequently, for the purposes of this section, a number of illustrations are provided indicating the capabilities of each energy storage technology in relation to one another, see Figure 6-1 to Figure 6-5. This is followed by a table specifying the applications that each storage technology is suitable for, see Table 6-1, which have been defined earlier in section 4. Finally, there is a table outlining the detailed characteristics of each storage technology (see Table 6-2) and a table indicating the cost of each technology (see Table 6-3).

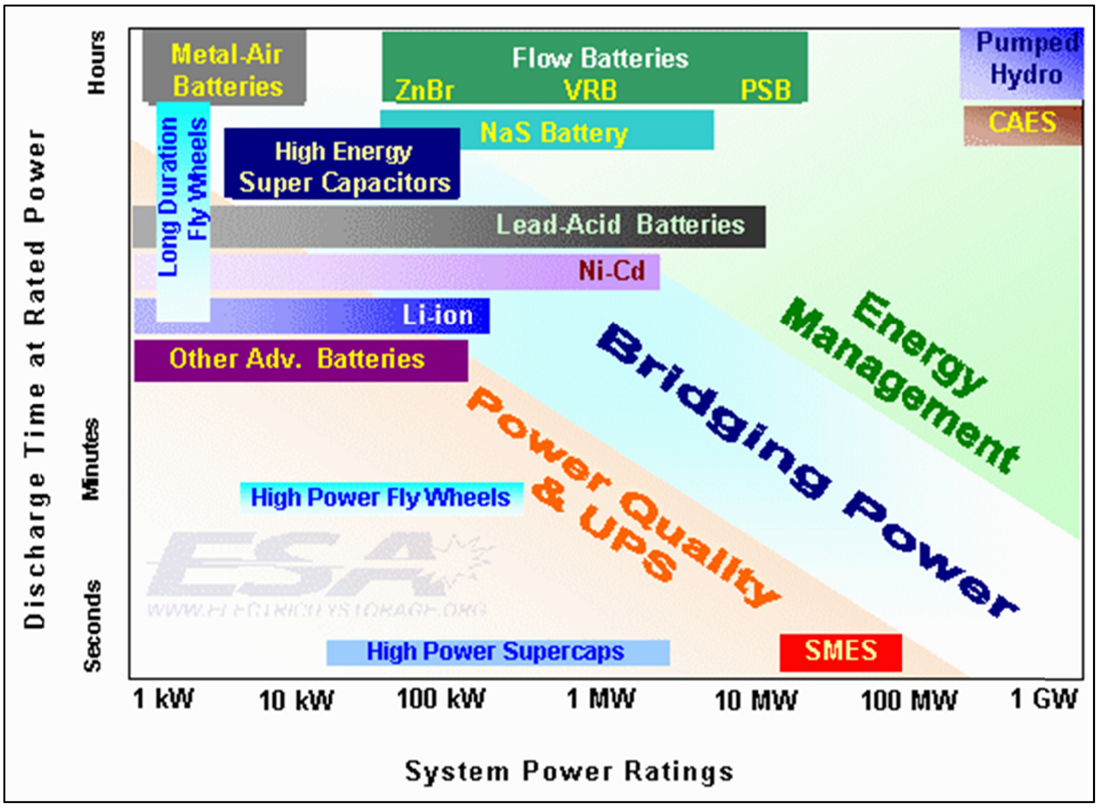


Figure 6-1: Discharge Time vs. Power Ratings for each storage technology [63].

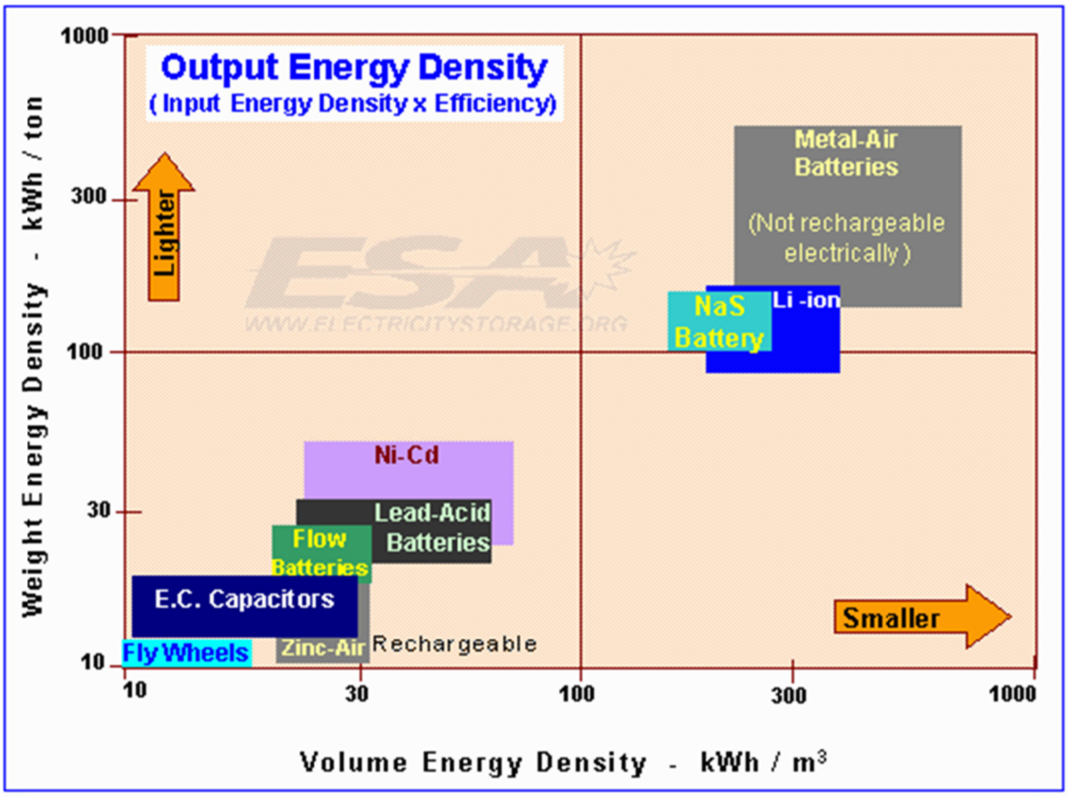


Figure 6-2: Weight Energy Density vs. Volume Energy Density for each technology [63].

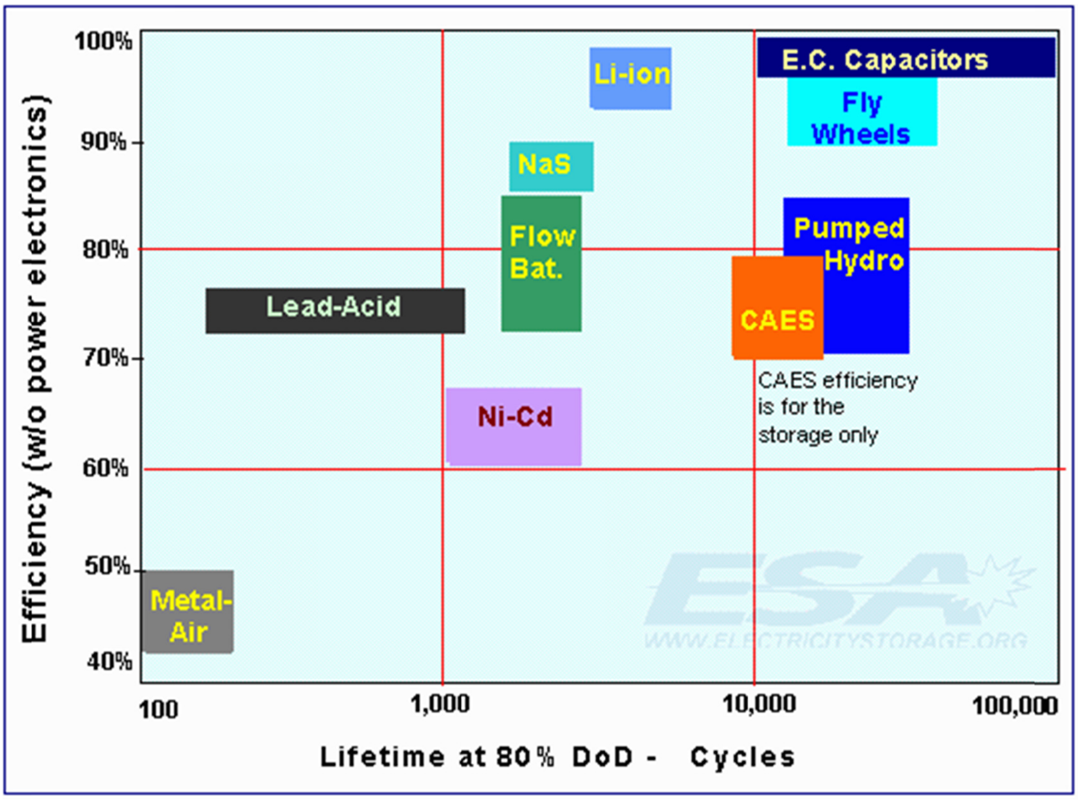


Figure 6-3: Efficiency & Lifetime at 80% DoD for each technology [63].

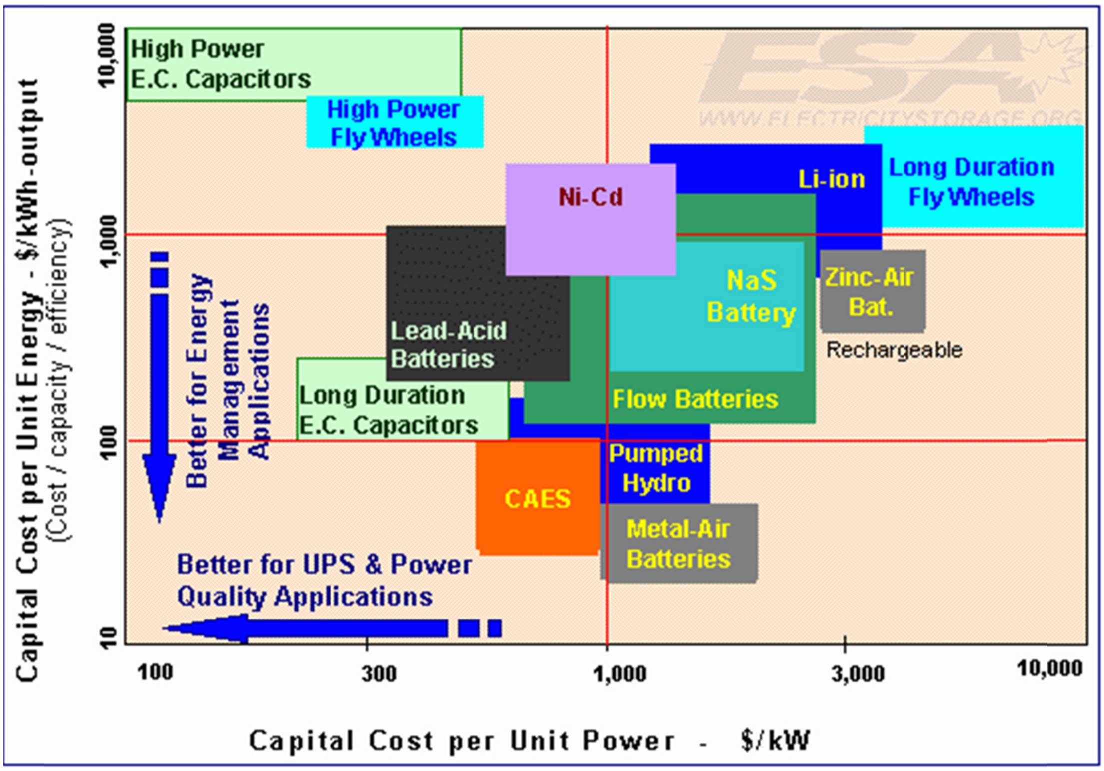


Figure 6-4: Capital Cost for each technology [63].

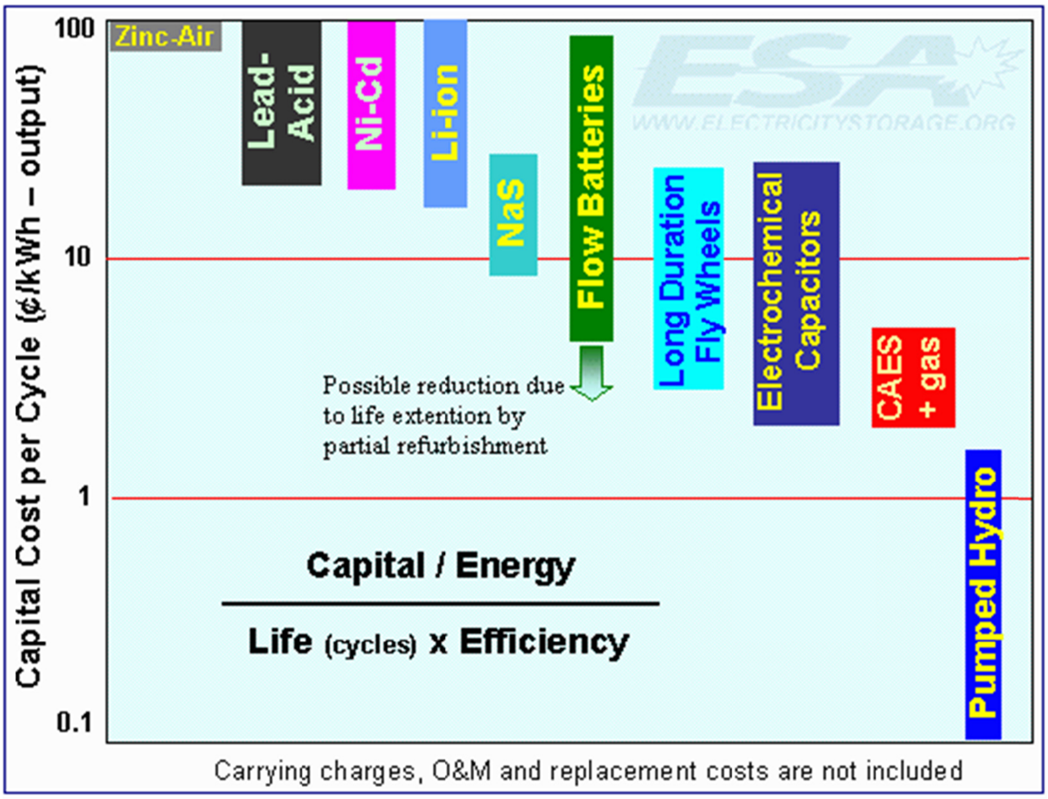


Figure 6-5: Cost per cycle for each technology [63].

Table 6-1: Technical suitability of storage technologies to different applications [2, 30, 64, 65].

	Storage Technology	Pumped hydro	Underground pumped hydro	Compressed air	Lead-acid batteries	Advanced batteries	Flow batteries	Flywheels	Supercapacitors	Superconducting magnetic	Hydrogen fuel cell	Hydrogen engine
Storage Application												
Transit and end-use ride-through					X		X	X	X	X	X	
Uninterruptible power supply					X	X	X	X			X	X
Emergency back-up		X	X	X	X	X	X				X	X
T&D stabilisation and regulation		X	X	X	X		X			X	X	
Load levelling		X	X	X	X	X	X				X	X
Load following		X	X	X	X	X	X				X	X
Peak generation		X	X	X	X	X	X	X			X	X
Fast response spinning reserve		X	X	X	X	X	X	X			X	X
Conventional spinning reserve		X	X	X	X	X	X	X			X	X
Renewable integration		X	X	X	X	X	X	X			X	
Renewables back-up		X	X	X	X	X	X				X	

Table 6-2: Characteristics of storage technologies [2, 8, 18, 47, 63].

Technology	Power rating	Discharge duration	Response time	Efficiency (%)	Parasitic losses	Lifetime	Maturity
Pumped hydro	100 – 4000 MW	4 – 12 h	sec - min	70 - 85	Evaporation	30 – 50 y	Commercial
Underground pumped hydro	100 – 4000 MW	4 – 12 h	sec – min	70 – 85	Evaporation	30 – 50 y	Concept
Compressed air (in reservoirs)	100 – 300 MW	6 – 20 h	sec - min	64	-	30 y	Commercial
Compressed air (in vessels)	50 – 100 MW	1 – 4 h	sec - min	57	-	30 y	Concept
Lead-acid battery	< 50 MW	1 min – 8 h	< ¼ cycle	85	Small	5 – 10 y	Commercial
Nickel-cadmium battery	< 50 MW	1 min – 8 h	n/a	60 – 70	~2 - 5%	3500 cycles	Commercial
Sodium-sulphur battery	< 10 MW	< 8 h	n/a	75 - 86	5 kW/kWh	5 y	In development
Vanadium-redox flow battery	< 3 MW	< 10 h	n/a	70 - 85	n/a	10 y	In test
Polysulphide-bromide flow battery	< 15 MW	< 20 h	n/a	60 - 75	n/a	2000 cycles	In test
Zinc-bromine flow battery	< 1 MW	< 4 h	< ¼ cycle	75*	Small	2000 cycles	In test / commercial units
Low-speed flywheel	< 1650 kW	3 – 120 s	< 1 cycle	90	~1%	20 y	Commercial products
High-speed flywheel	< 750 kW	< 1 h	< 1 cycle	93	~3%	20 y	Prototypes in testing
Supercapacitor	< 100 kW	< 60 s	< ¼ cycle	95	-	10000 cycles	Some commercial products
Superconducting magnetic (Micro)	10 kW – 10 MW	1 – 60 s	< ¼ cycle	95	~4%	30 y	Commercial
Superconducting magnetic	10 – 100 MW	1 – 30 min	< ¼ cycle	95	~1%	30 y	Design concept
Hydrogen (fuel cell)	< 250 kW**	As needed	< ¼ cycle	34 - 40	n/a	10 – 20 y	In test
Hydrogen (engine)	< 2 MW**	As needed	Seconds	29 – 33	n/a	10 – 20 y	Available for demonstration

*AC-AC Efficiency
**Discharge device. An independent charging device (electrolyser) is required.

Table 6-3: Costs of storage technologies [2, 8, 18, 47, 63].

	Capital cost			O&M cost				
Technology	Power related cost ($/kW)	Energy related cost ($/kWh)	BOP ($/kWh)	Fixed ($/kW-y)	Variable (c$/kWh)	Cost certainty	Environmental issues	Safety issues
Pumped hydro	600 - 2000	0 – 20	Included	3.8	0.38	Price list	Reservoir	Exclusion area
Underground pumped hydro	n/a	n/a	n/a	3.8	0.38	Estimate	Reservoir	Exclusion area
Compressed air (in reservoirs)	425 - 480	3 - 10	50	1.42	0.01	Price quotes	Gas emissions	None
Compressed air (in vessels)	517	50	40	3.77	0.27	Estimate	Gas emissions	Pressure vessels
Lead-acid battery	200 - 580	175 - 250	~50	1.55	1	Price list	Lead disposal	Lead disposal, H_2
Nickel-cadmium battery	600 – 1500	500 – 1500	n/a	n/a	n/a	Estimate	Toxic cadmium	Toxic cadmium
Sodium-sulphur battery	259 - 810	245	~40	n/a	n/a	Project specific	Chemical handling	Thermal reaction
Vanadium-redox flow battery	1250 – 1800	175 - 1000	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Polysulphide-bromide flow battery	1000 - 1200	175 - 190	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Zinc-bromine flow battery	640 - 1500	200 - 400	Included	n/a	n/a	Project specific	Chemical handling	Chemical handling
Low-speed flywheel	300	200 - 300	~80			Price list	-	Containment
High-speed flywheel	350	500 - 25000	~1000	7.5	0.4	Project specific	-	Containment
Supercapacitor	300	82000	10000	5.55	0.5	Project specific	-	-
Superconducting magnetic (Micro)	300	72000	~10000	26	2	Price quotes	-	Magnetic field
Superconducting magnetic	300	2000	~1500	8	0.5	Estimate	-	Magnetic field
Hydrogen (fuel cell)	1100 - 2600	2 - 15	n/a	10	1	Price quotes	-	-
Hydrogen (engine)	950 – 1850	2 - 15	n/a	0.7	0.77	Price list	Emissions	-

6.5 Energy storage systems

As energy systems transform from a fossil fuel system based on centralised production, to a renewable energy system, based on intermittent decentralised production, it is imperative that system flexibility is maximised. An ideal option to achieve this is by integrating the three primary sectors within any energy system: the electricity, heat and transport sectors. HESS, TESS, and EV's provide unique opportunities to integrate these three sectors and hence increase the renewable energy penetrations feasible. However, it is difficult to compare HESS, TESS and EV's to the other energy storage technologies directly as energy storage is only part of the system they are composed of.

The HESS provides an excellent level of flexibility within an energy system, by enabling the electricity, heat and transport sectors to interact with one another. However, the primary disadvantage is the poor efficiencies achieved due to the number of conversions required between creating hydrogen and using hydrogen. In contrast, the TESS increases the efficiency of the overall energy system by replacing conventional power plants with CHP. However, TESS does not incorporate the transport sector. As a result, EVs (the third energy system discussed) are often combined with the TESS. This has been analysed in a separate study which compared a HESS and a combined TESS/EV energy system [61, 62]. It was found that the TESS/EV energy system only needs 85% of the fuel that a HESS requires [61, 62]. In addition, the TESS has already been implemented in Denmark and thus is a much more mature solution that a hydrogen economy. However, in the long-term if baseload renewable energy (i.e. biomass) is limited, the inefficiencies of the hydrogen energy system may be an attractive replacement. Therefore, a lot of potential exists but more research is required to truly quantify the benefits and drawbacks of each system.

Finally, it is evident from the research carried out to date that energy storage systems could be a more promising solution for the integration of intermittent renewable energy than individual technologies. Energy storage technologies will most likely improve the penetrations of renewable energy on the electricity network, but often disregard the heat and transport sectors. Consequently, it is imperative that uncertainties surrounding the costs and potential of energy storage systems are investigated, considering the promise they possess relative to the stand-alone technologies.

7 Conclusions

No one technology has all the ideal characteristics required for optimal grid integration of renewables. By looking at the energy storage systems used during island[1] investigations, it becomes apparent that very large storage capacities are necessary to obtain high wind penetrations (>90%). Bakos [66] and Kaldellis [67] concluded that a storage capacity in the region of 1 to 3 days of the electricity grids power requirement is necessary to obtain wind penetrations above 90%. Although larger energy systems will probably require less energy storage than island systems, primarily due to the possibilities of creating additional flexible loads such as electric vehicles or demand side management (DSM), these island case studies indicate that large-scale energy storage capacities will most likely be necessary if energy storage is used for integration fluctuating renewable penetrations.

Pumped hydroelectric energy storage (PHES) is the largest and most mature form of energy storage available. It is widely believed that suitable locations to construct PHES facilities are becoming rare [21-25], which has become the primary weakness for PHES development in recent years. However, as recent reports illustrate that Ireland has many more suitable PHES sites than originally anticipated [26-29], it was concluded from this review that PHES is the most likely stand alone energy storage technology that will be utilised in the coming years for the integration of fluctuating renewable energy.

In addition to PHES, all three energy storage systems discussed in this report warrant further investigate primarily based on their potential to improve renewable energy penetrations in the future. The hydrogen energy storage system (HESS) is evolving rapidly especially in the transport sector. Even if hydrogen is not used to generate electricity, it could still be required in the future for other applications such as heating or transport. Therefore, it is an area that has a lot of future potential even though it can be an inefficient process. The thermal energy storage system (TESS) is not only capable of increasing the wind penetration feasible within an energy system, but it also increases the overall efficiency of the energy system. Even more importantly, this technology has already been proven within the Danish energy system and hence does not carry the same risks as other alternatives. However, the primary drawback of the TESS in comparison to the HESS is the transport sector: TESS does not account for the transport sector. However, this can be overcome by combining the TESS with electric vehicles (EVs). Electric vehicles (EVs) are more efficient than both hydrogen and conventional vehicles. They also have the potential to make large-scale battery energy storage economical and hence vastly improve the flexibility within an energy system. By combining EVs with the TESS, the overall fuel demand can be reduced and fluctuating renewable energy penetrations can be increased. Also, Lund and Mathiesen have shown that this technique can be extended further to create a 100% renewable energy system [57]. As a result, this combination is one of the most promising solutions to in the transition from a fossil fuel to a renewable based energy system.

In relation to the other technologies discussed in this report, BES, FES, SMES, SCES, and ACTES are will most likely be used in some form within the power sector in the future, but major operational breakthroughs are unlikely. FBES is another potential option for the future, but it may not have the scale necessary to co-exist with a successful rollout of EVs. In some countries CAES might be more feasible than PHES for large-scale storage due to the availability of suitable sites. However, due to the number of potential sites currently being identified in Ireland, PHES is the most attractive large-scale energy storage technology for the Irish energy system for the integration of fluctuating renewable energy.

To conclude, from a stand-alone perspective, PHES will most likely be the most attractive option in years to come for Ireland, but it is also imperative that uncertainties surrounding the HESS, TESS, and EVs are also assessed based on the potential flexibility they can also create.

[1]Island energy-systems refers to small-scale stand-alone energy systems where the installed generating-capacities ranging from 1 to 10 MW.

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